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Environmental Assessment of NOx Control on a Spark-Ignited Large Bore Reciprocating Internal Combustion Engine Volume 1. Technical Results

Acurex Corp., Mountain View, CA

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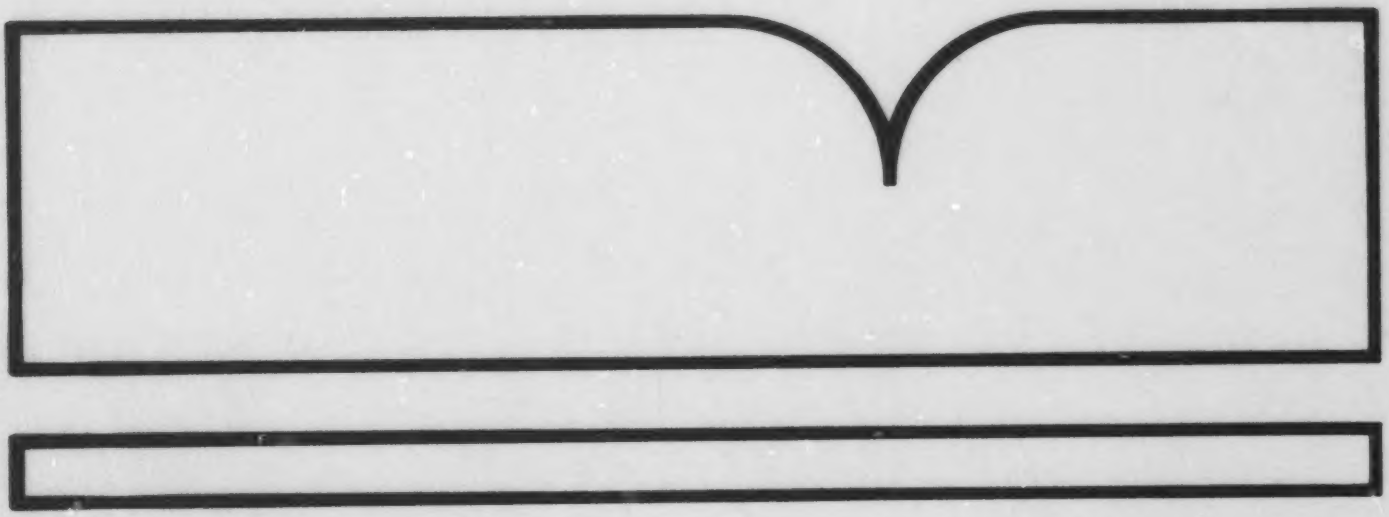

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ENVIRONMENTAL ASSESSMENT OF NO_x CONTROL ON A SPARK-IGNITED LARGE BORE RECIPROCATING INTERNAL COMBUSTION ENGINE

Volume I
Technical Results

by

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16. ABSTRACT Volume I of this report gives emission results for a spark-ignited, large-bore, reciprocating, internal-combustion engine operating both under baseline (normal) conditions, and with combustion modification controls to reduce NOx emissions to levels below the proposed new source performance standard (NSPS) for such engines. Exhaust gas measurements included (in addition to continuous monitoring of criteria gas emissions) total organics in two boiling point ranges, compound category information within these ranges, specific quantitation of semivolatile organic priority pollutants, flue gas concentrations of 73 trace elements, and particulates. Exhaust NOx emissions were reduced almost 50 percent, from a baseline level of 1,260 ng/J (730 to 420 ppm corrected to 15 percent O2 dry) by increasing the operating air/fuel ratio of the engine. Accompanying this reduction was a slight increase in engine efficiency. CO, methane, total hydrocarbon, and total semivolatile organic compound emissions were increased from 10 to 65 percent under low-NOx operation. However, total nonvolatile organic emissions decreased 55 percent. The organic emissions for both tests consisted primarily of aliphatic hydrocarbons with some carboxylic acids, phenols, and low-molecular-weight fused-ring aromatics. POMs were detected in concentrations below 4 micrograms/dscm.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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SECTION 1

INTRODUCTION

This report describes and presents results for a set of environmental assessment tests performed for the Environmental Protection Agency's Air and Energy Engineering Research Laboratory (EPA/AEERL), Research Triangle Park, under the Combustion Modification Environmental Assessment (CMEA) program, EPA Contract No. 68-02-3188. The CMEA started in 1976 with a 3-year study, the NO_x Control Technology Environmental Assessment (NO_x EA, EPA Contract No. 68-02-2160), having the following four objectives:

- Identify potential multimedia environmental effects of stationary combustion sources and combustion modification technologies
- Develop and document control application guidelines to minimize these effects
- Identify stationary source and combustion modification R&D priorities
- Disseminate program results to intended users.

During the first year of the NO_x EA, data for the environmental assessment were compiled and methodologies were developed. Furthermore, priorities for the schedule and level of effort to be devoted to evaluating the various source/fuel/control combinations were identified. This effort revealed major data gaps, particularly for noncriteria pollutants (organic emissions and trace elements) for virtually all combinations of stationary

combustion sources and combustion modification techniques. Consequently, a series of seven environmental field test programs were undertaken to fill these data gaps. The results of these tests are documented in seven individual reports (References 1-1 through 1-7) and in the NO_x EA final report summarizing the entire 3-year effort (Reference 1-8).

The current CMEA program has, as major objectives, the continuation of multimedia environmental field tests initiated in the original NO_x EA program. These new tests, using standardized Level 1 sampling and analytical procedures (Reference 1-9) are aimed at filling the remaining data gaps and addressing the following priority needs:

- Advanced NO_x controls
- Alternate fuels
- Secondary sources
- EPA program data needs
  - -- Residential oil combustion
  - -- Wood firing in residential, commercial, and industrial sources
  - -- High interest emissions determination (e.g., listed and candidate hazardous air pollutant species)
- Nonsteady-state operation

A spark-ignited natural gas-fired stationary reciprocating internal combustion engine (ICE) was selected for multimedia environmental tests under the CMEA program. The objectives of the tests were to quantify multimedia emissions from the engine operating without NO_x controls and during controlled operation with combustion modifications. Prior field tests for multimedia emissions on ICE's using Level 1 procedures have been limited to uncontrolled engine operation (Reference 1-10). The data presented in this

report quantify the multimedia environmental impact of combustion modification NO_x controls on a large bore gas engine and identify pollutants of concern using results from standardized sampling and analytical procedures.

Concurrent with this test program, a compression ignition engine burning diesel fuel was tested to evaluate the impact of NO_x control on this engine type. Results of this test are documented in another report under the current CMEA program (Reference 1-11). Table 1-1 lists all sources tested to date in the CMEA effort, outlining the combustion modification controls implemented and the level of sampling and analysis performed in each case. Results of these test programs are discussed in separate reports available through EPA.

TABLE 1-1. COMPLETED TESTS DURING THE CURRENT PROGRAM

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Spark ignited natural gas-fired reciprocating internal combustion engine	Large bore, 6-cylinder, opposed piston, 186 kW (250 Bhp)/cyl, 900 rpm, Model 38TDS8-1/8	-- Baseline (pre-NSPS) -- Increased air-fuel ratio aimed at meeting proposed NSPS of 700 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Compression ignition diesel-fired reciprocating internal combustion engine	Large bore, 6-cylinder opposed piston, 261-kW (350 Bhp)/cyl, 900-rpm, Model 38TDD8-1/8	-- Baseline (pre-NSPS) -- Fuel injection retard aimed at meeting proposed NSPS of 600 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 8 -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Low-NO_x residential condensing heating system furnished by Karlsons Blueburner Systems Ltd. of Canada	Residential hot water heater equipped with M.A.N. low-NO_x burner, 0.55 ml/s (0.5 gal/hr) firing capacity, condensing flue gas	Low-NO_x burner design by M.A.N.	Furnace exhaust: -- SASS -- Method 8 -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Waste water	New test
Rocketdyne/EPA low-NO_x residential forced warm air furnace	Residential warm air furnace with modified high pressure burner and firebox, 0.83 ml/s (0.75 gal/hr) firing capacity	Low-NO_x burner design and integrated furnace system	Furnace exhaust: -- SASS -- Method 8 -- Controlled condensation -- Method 5 -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel	New test

TABLE 1-1. CONTINUED

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Pulverized coal-fired utility boiler, Conesville station	400-MW tangentially fired; new NSPS design aimed at meeting 301 ng/J NO_x limit	ESP inlet and outlet, one test	ESP inlet and outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2 Coal Bottom ash ESP ash	Exxon Research and Engineering (ER&E) conducting corrosion tests
Nova Scotia Technical College industrial boiler	1.14 kg/s steam (9,000 lb/hr) firetube fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with limestone injection	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, CO_2, CO, NO Fuel	Envirocon performed particulate and sulfur emission tests
Adelphi University industrial boiler	1.89 kg/s steam (15,000 lb/hr) hot water firetube fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with Na_2CO_3 injection	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas Sample (C_1 - C_6 HC) -- Continuous O_2, CO_2, NO, CO Fuel	Adelphi University
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-oil (COM)	-- Baseline test only with COM	Boiler outlet: -- SASS -- Method 5 -- Controlled condensation -- Continuous O_2, CO_2, NO, TUHC, CO -- N_2O grab sample Fuel	PETC and General Electric (GE)

TABLE 1-1. CONTINUED

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
TOSCO Refinery vertical crude oil heater	2.54 Ml/day (16,000 bbl/day) natural draft process heater burning oil/refinery gas	-- Baseline -- Staged combustion using air injection lances	Heater outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO, CO, CO_2, HC -- N_2O, grab sample Fuel oil Refinery gas	KVB coordinating the staged combustion operation and continuous emission monitoring
Mohawk-Getty Oil industrial boiler	8.21 kg/s steam (65,000 lb/hr) watertube burning mixture of refinery gas and residual oil	-- Baseline -- Ammonia injection using the noncatalytic Thermal DeNO_x process	Economizer outlet: -- SASS -- Method 5, 17 -- Controlled condensation -- Gas Sample (C_1 - C_6 HC) -- Ammonia emissions -- N_2O grab sample -- Continuous O_2, NO, CO, CO_2 Fuels (refinery gas and residual oil)	New test
Industrial boiler	2.52 kg/s steam (20,000 lb/hr) watertube burning woodwaste	-- Baseline (dry wood) -- Green wood	Boiler outlet: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO, CO Fuel Flyash	North Carolina Department of Natural Resources, EPA IERL-RTP
Industrial boiler	3.16 kg/s steam (29,000 lb/hr) firetube with refractory firebox burning woodwaste	-- Baseline (dry wood)	Outlet of cyclone particulate collector: -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO_x, CO Fuel Bottom ash	North Carolina Department of Natural Resources, EPA IERL-RTP

TABLE 1-1. CONTINUED

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Enhanced oil recovery steam generator	15 MW (50 million Btu/hr) steam generator burning crude oil equipped with MHI low-NO_x burner	-- Performance mapping -- Low NO_x operation	Steamer outlet: -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO_x, CO, CO_2 -- N_2O grab sample Fuel	Getty Oil Company, CE-Natco
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-water (CWM)	-- Baseline test only with CWM	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1 - C_6 HC) -- Continuous O_2, NO_x, CO, CO_2, TUHC -- N_2O grab sample Fuel Bottom ash Collector hopper ash	PETC and General Electric
Spark-ignited, natural gas fueled internal combustion engine equipped with nonselective NO_x reduction catalyst	610 kW (818 HP) Waukesha engine equipped with DuPont NSCR catalyst	-- Controlled with NSCR -- 15-day emissions monitoring	Catalyst inlet and outlet -- SASS -- NH_3 -- HCN -- N_2O grab sample -- Continuous O_2, CO_2, NO_x, TUHC Fuel	Southern California Gas Company

TABLE 1-1. CONCLUDED

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Industrial boiler	180 kg/hr steam (400 lb/hr) stoker fired with a mixture of coal and waste plastic beverage containers	-- Baseline (coal) -- Coal and plastic waste	Boiler outlet -- SASS -- VOST -- Method 5/8 -- HCl -- Continuous O_2, NO_x, CO, CO_2, TUHC -- N_2O grab sample Fuel Bottom ash Cyclone ash	Vermont Agency of Environmental Conservation
Industrial boiler	7.6 kg/s steam (60,000 lb/hr) watertube retrofit for coal-water slurry firing	-- Baseline test with (CWS) -- 30-day emission monitoring	Boiler outlet -- SASS -- VOST -- Method 5/8 -- Grab sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous NO_x, CO, CO_2, O_2, TUHC, SO_2 Fuel	EPRI, DuPont
Enhanced oil recovery steam generator	15 MW (50 million Btu/hr) steam generator burning crude oil, equipped with the EPA/EER low-NO_x burner	-- Low NO_x (with burner) -- 30-day emission monitoring	Steamer outlet -- SASS -- VOST -- Method 5/8 -- Controlled condensation -- Anderson impactors -- Grab sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous NO_x, CO, CO_2, O_2, SO_2 Fuel	Chevron U.S.A., EERC

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SECTION 2

TEST ENGINE DESCRIPTION

The test program was conducted on an 1,120 kW (1,500 Bhp), two-stroke, opposed piston spark-ignited Model 38TDS8-1/8 engine manufactured by the Fairbanks Morse Engine Division of Colt Industries. Figure 2-1 illustrates the piston arrangement of this spark-ignited engine which utilizes no cylinder heads or valves. The air-fuel mixture is compressed between the two pistons which work vertically towards each other in each cylinder. The upper and lower pistons drive separate crankshafts interconnected by a vertical drive. The vertical drive connection is made with the lower crankshaft advanced in operating position ahead of the upper crankshaft. This difference in crankshaft positions is called "Lower Crank Lead." A diagram of piston positions in the two-cycle spark-ignited engine is shown in Figure 2-2.

This spark-ignited engine is normally marketed by Colt Industries as a blower-scavenged design. However, the test engine used for emissions evaluation in this program was equipped with a turbine driven turbocharger for improved efficiency. A schematic of the turbo-blower design of the test engine is illustrated in Figure 2-3.

The combustion air is drawn into the turbocharger, where it is compressed and discharged through an air cooler to the positive displacement lobe-type blower. The blower is driven by the upper engine crankshaft. The

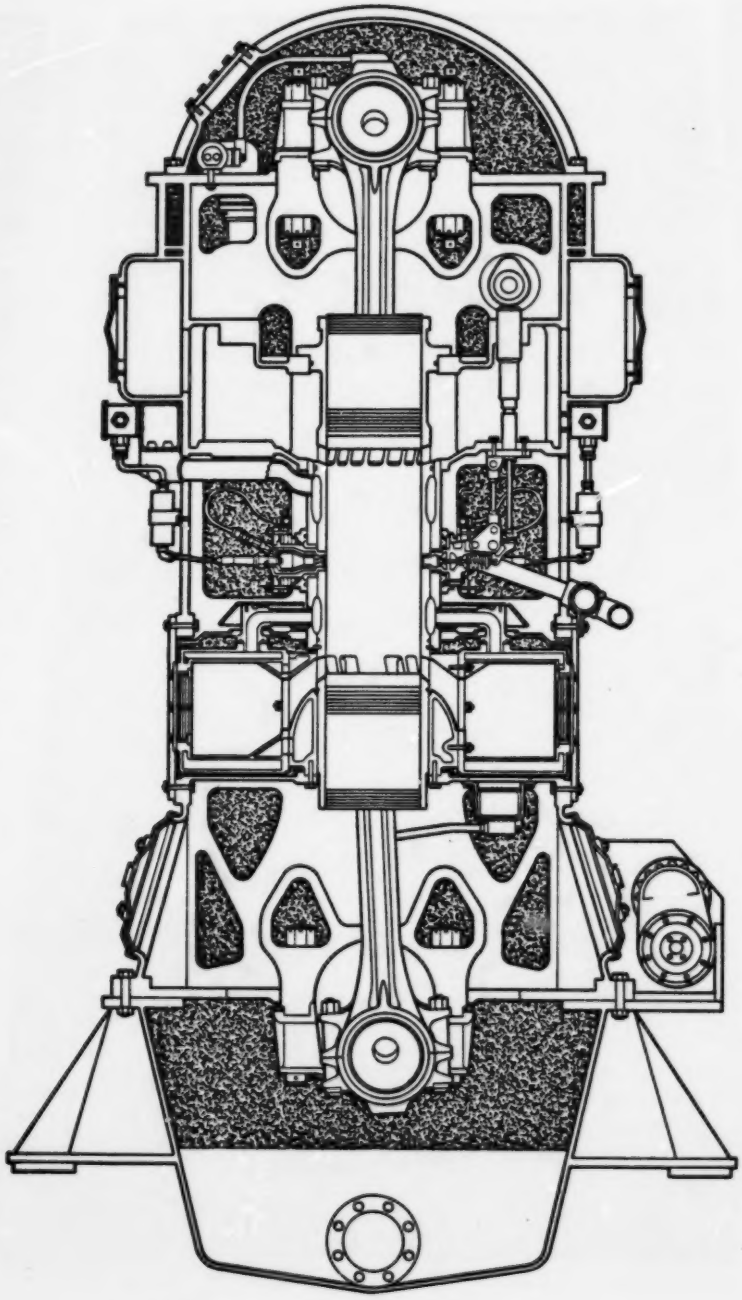


Figure 2-1. Cross section of opposed piston spark-ignited Model 38DS8-1/8 engine (courtesy of Fairbanks Morse Division of Colt Industries).

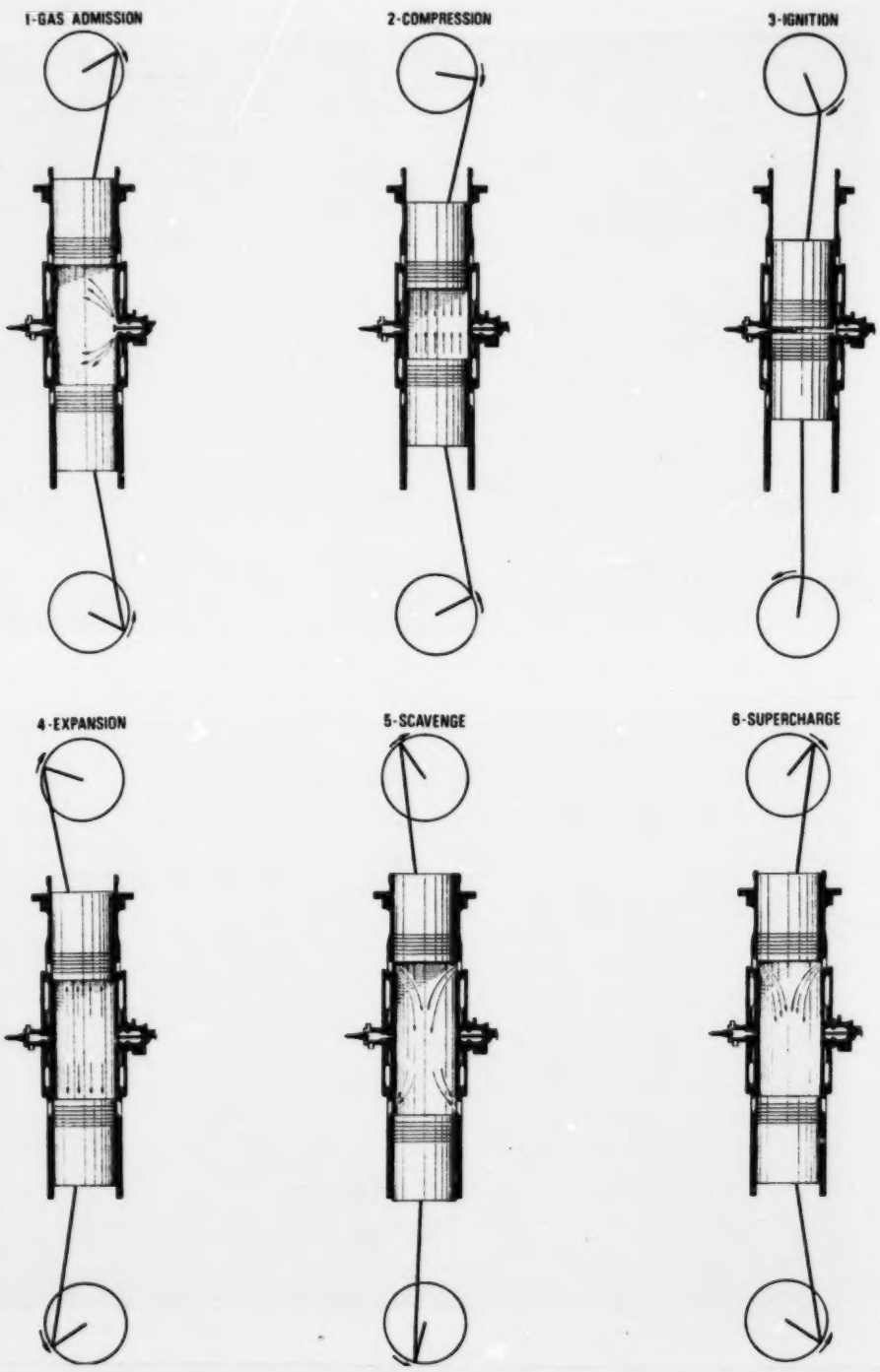
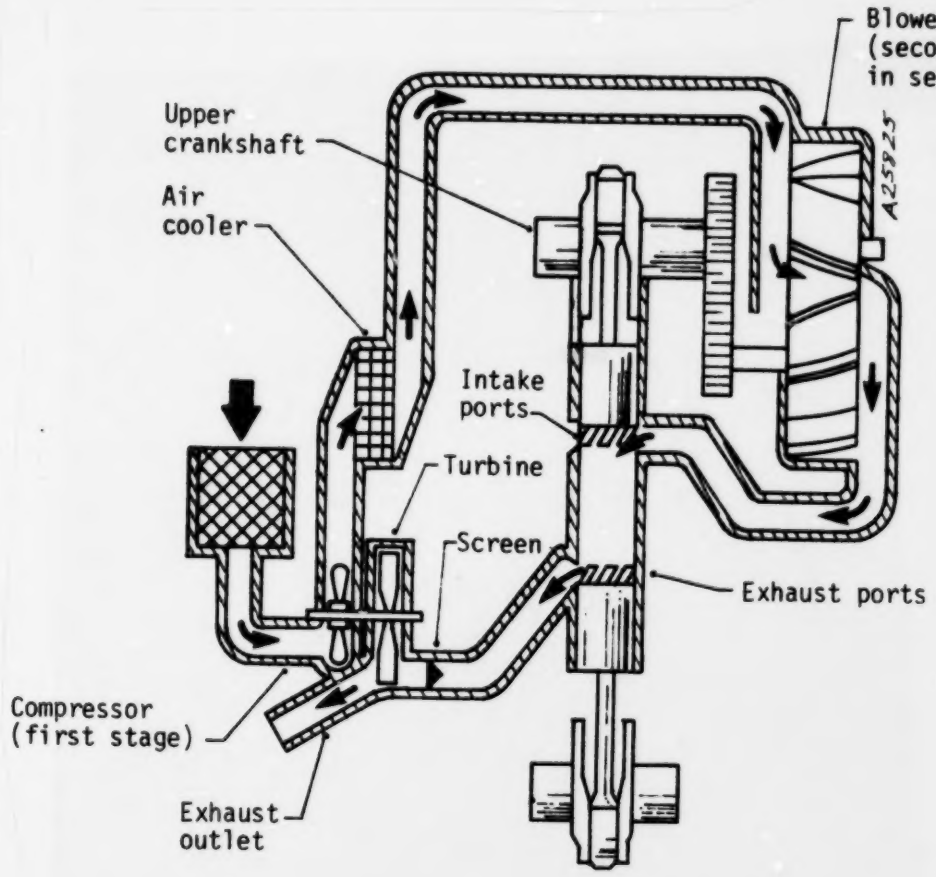


Figure 2-2. Cycle diagram -- opposed piston spark-ignited engine (courtesy of Fairbanks Morse Division of Colt Industries).



Schematic of turbo-blown arrangement

Figure 2-3. Schematic of turbo-blower arrangement (courtesy of Fairbanks Morse Division of Colt Industries).

air from the blower is then discharged directly to the cylinders through the engine intake manifold. The inlet air both scavanges the cylinder (sweeping all combustion products from the compression chamber) as well as supplying sufficient charge for the next combustion cycle. Hot exhaust gas leaving from the lower cylinder ports serves to drive the turbine of the turbocharger assembly.

The fuel is ignited with spark ignition cells, arranged two per cylinder. The dual cell system assures optimum cylinder firing pressure on both sides of the engine at all engine speeds and torques. An illustration of a spark ignition cell is presented in Figure 2-4.

Table 2-1 summarizes the design specifications of the engine tested in the program. As indicated, the engine has six cylinders with a displacement of 0.017 m^3 (1,037 $in.^3$) per cylinder. The ignition timing of the ignition cells is set at 4.5 crankshaft degrees before minimum cylinder volume (BMV). The two-stroke engine configuration indicates that the power cycle is completed in one revolution of the crankshaft as compared with two revolutions for a four-stroke type. In addition to the natural gas fuel, the engine also consumes lubrication oil at a rate of one liter per 2.48 GJ (1 gallon per 3,500 Bhp-hr). At design operating load, of 1,120 kW (1,500 Bhp) at 900 rpm, lube oil consumption is about 1.65 l/h (0.43 gph), representing approximately 0.6 percent of the total heat supplied to the engine.

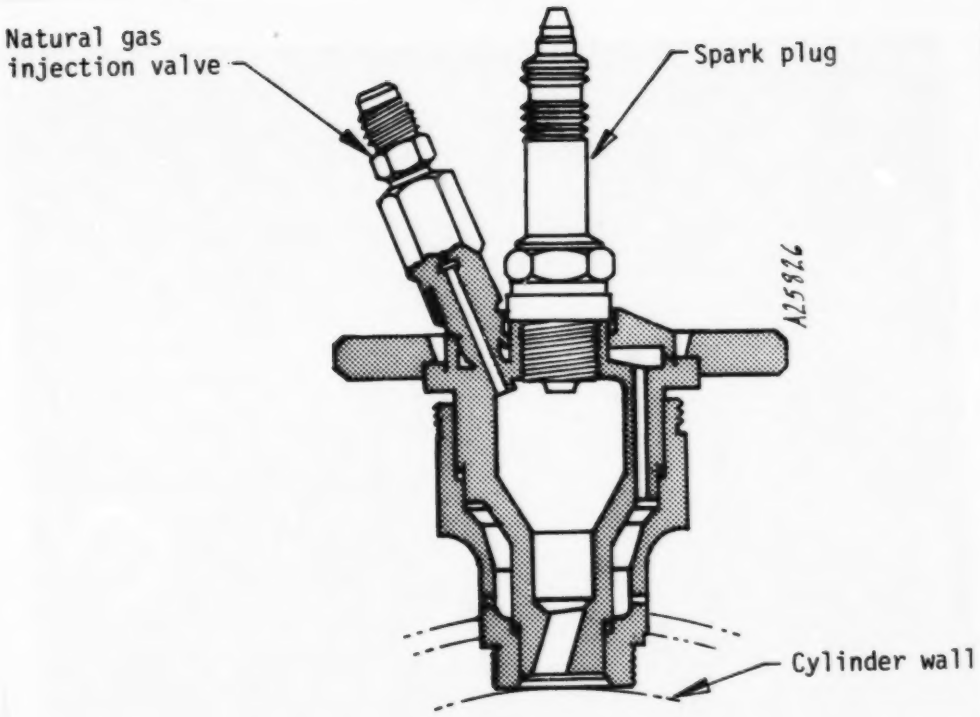


Figure 2-4. Natural gas spark ignition cell.

TABLE 2-1. TURBOCHARGED SPARK ENGINE SPECIFICATION

Model Designation	38TDS8-1/8
Serial Number	889193
Configuration	2 Stroke, O.P.
Bore	0.206 m (8-1/8 in.)
Stroke	0.254 m (10 in.) x 2
Number of Cylinders	6
Displacement/Cyl	0.017 m^3 (1,037 $in.^3$)
Compression Ratio	9.7:1
BMEP	731 kPa (106 psi)
Bhp/Cylinder at rpm	186 kW (250 Bhp) at 900 rpm
Hours Since Overhaul	1050
Spark Timing	4.5° BMV
Lubricating Oil	Pegasus 485
L.O. Consumption	1 l/2.48 GJ (1 gal/3,500 Bhp-hr)

SECTION 3

NO_x CONTROL AND EMISSIONS RESULTS

Exhaust gas emissions from the spark-ignited engine were measured during two separate tests: (1) under baseline engine operating conditions and (2) with NO_x combustion modification controls for reducing NO_x. Section 3.1 summarizes engine operating conditions, describes the combustion modifications applied to reduce NO_x emissions and other test variables, and discusses the impact of the NO_x control on engine operation. Sections 3.2 through 3.3 summarize emission results by major category of pollutants (i.e., criteria pollutants and other gas phase species in section 3.2, trace element species in section 3.3, and organic emissions in section 3.4). Results of bioassay analyses of the exhaust gas sample organic extract and discussion of the potential environmental impact of NO_x control are summarized in section 4.

3.1 ENGINE OPERATING PARAMETERS AND TEST VARIABLES

Table 3-1 lists operating parameters of the test engine for the baseline and the controlled NO_x tests. Atmospheric conditions of temperature, humidity, and pressure are also presented as these affect the level of NO_x emitted by the engine.

Engine power output was nearly constant at a near maximum rating for the duration of both tests. RPM and ignition timing were set at rated settings. As indicated in Section 2, this engine model has generally been marketed

TABLE 3-1. ENGINE OPERATING PARAMETERS AND AMBIENT ATMOSPHERIC CONDITIONS -- SPARK-IGNITED ENGINE

Parameter	Baseline test	NO_x control test
Engine Parameter		
RPM (percent rating)	900 (100%)	900 (100%)
kW_t (Bhp) (percent rating)	1,117 (1,498) (99.8%)	1,123 (1,505) (100%)
kW_e (percent rating)	1,085 (97.8%)	1,091 (98.9%)
BMEP, kPa (psi)	731 (106)	731 (106)
Fuel Flow, m^3/h (ft^3/hr)	354 (12,492)	352 (12,426)
BSFC, g/kW-hr (lb/Bhp-hr)	217 (0.356)	215 (0.353)
Fuel Rate, kW fuel/kW out (Btu/Bhp-hr)	2.91 (7,413)	2.88 (7,340)
Ignition Timing	4.5° BMV	4.5° BMV
Compressor Inlet Air Temp., K (°F)	302 (85)	302 (85)
Compressor Outlet Air Temp., K (°F)	356 (181)	359 (187)
Manifold Air Cooling Bypass, percent	16.4	0
Blower Suction Air Temp., K (°F)	331 (136)	316 (110)
Blower Discharge Air Temp., K (°F)	345 (161)	337 (146)
Blower Discharge Pressure, kPa (psig)	60 (8.7)	71 (10.3)
Air Flow, kg/s (lb/min)	2.56 (338.3)	2.90 (383.4)
Fuel-Air Ratio	0.0271	0.0240
Combined Cylinder Exhaust Temp., K (°F)	732 (858)	699 (799)
Turbine Exhaust Temp., K (°F)	652 (715)	617 (652)
Lube Oil Consumption, ml/s (gph)	0.45 (0.43)	0.45 (0.43)
Engine Efficiency, percent	34.3	34.7
Average Ambient Atmospheric Conditions		
Outdoor Temp. Dry bulb, K (°F)	281 (46)	284 (51)
Barometric pressure, kPa (in Hg)	98.2 (29.08)	98.6 (29.20)
Humidity, percent	60	62

without the turbocharger and manifold air cooler. Turbocharging and aftercooling increase the air-fuel ratio, generally resulting in lower NO_x levels compared to a blower-scavanged spark-ignited engine. To reduce the effect of turbocharging during the baseline test, a portion of the combustion air was bypassed around the manifold air cooler. The resulting increase in combustion air temperature lowered the air mass flowrate, resulting in an air-fuel ratio which is more representative of the blower-scavanged design. The percent air cooler bypass during the baseline test was 16.4 percent, determined by the air flow control limits available on this test engine. Thus, baseline engine operation was as representative of the operation of a typically marketed (blower-scavenged) engine as could be achieved with the turbocharger in place.

Combustion modification NO_x control during the low-NO_x test consisted of an increase in air-fuel ratio from 36.9 to 41.7 kg air/kg fuel, a 13 percent increase from the baseline level. This increase in air-fuel ratio was accomplished by eliminating the manifold air cooler bypass used during the baseline test and increasing the combustion air cooling efficiency. The difference in combustion air temperatures between both tests can be noticed in the blower suction and discharge temperatures which measured, respectively, 331K and 345K (136°F and 161°F) at baseline, and 316K and 336K (110°F and 146°F), respectively, during the low-NO_x test. The lower combustion air temperature increased the mass flow of combustion air from 2.56 kg/s (338.3 lb/min) to 2.90 kg/s (383.4 lb/min), resulting in an increase in blower discharge pressure from 60 kPa (8.7 psi) to 71 kPa (10.3 psi).

The increase in air-fuel ratio resulted in an increase in engine efficiency of about 0.4 percent. In order to maintain engine rated power output, fuel flow was reduced during the low-NO_x test. Natural gas flow was reduced from 354 m^3/h (12,490 ft^3/hr) to 352 m^3/h (12,430 ft^3/hr), representing a reduction in heat input of 0.53 percent. The total increase in engine efficiency resulted from the combined effect of increasing power output from 1,498 Bhp to 1,505 Bhp and reducing fuel flowrate.

Average ambient atmospheric conditions did not vary significantly between the two tests, each conducted on a separate day. Percent relative humidity increased slightly from 60 to 62 percent, corresponding to an increase of 0.004 kg water/kg air at given ambient dry bulb temperatures. Inlet temperature to the turbocharger was artificially maintained at a constant 302K (85°F) by means of a heat exchanger. This constant temperature of combustion air at the compressor inlet eliminates the need to correct NO_x emissions to a standard temperature.

3.2 CRITERIA POLLUTANT AND OTHER GAS PHASE SPECIES EMISSIONS RESULTS

Table 3-2 summarizes gaseous and particulate emissions measured during baseline and low-NO_x engine operation. Gaseous species emissions were measured with a continuous monitoring sampling system in accordance with the exhaust emission measurement procedure published by the Diesel Engine Manufacturer Association (DEMA) (Reference 3-1). Particulate emissions were sampled with a High Volume Sampling System (HVSS) in accordance with EPA Reference Method 5 procedures. Both solid and condensable particulate mass loadings are reported. Particulate mass emissions were also calculated from samples collected with the Source Assessment Sampling System (SASS). The SASS train is used primarily for collection of samples for analysis of trace

TABLE 3-2. CRITERIA AND OTHER GAS SPECIES EMISSIONS FROM SPARK-IGNITED ENGINE DURING BASELINE AND LOW-NO_x TEST

Pollutant	Baseline			Low-NO_x[a]		
As measured by continuous gas analyzers[b]:						
O_2, percent	12.1			13.2		
CO_2, percent	4.9			4.4		
NO, ppm	976			480		
NO_x, ppm	1,040			510		
CO, ppm	170			253		
CH_4, ppm	721			725		
TUHC, ppm as C_3H_8	877			895		
Smoke spot (Bosch)	0			0		
Corrected gaseous emissions:	ppm[c]	ng/J[d]	g/Bhp-hr[e]	ppm[c]	ng/J[d]	g/Bhp-hr[e]
NO[f]	684	1,180	9.26	398	690	5.34
NO_x[f]	729	1,260	9.87	423	654	5.06
CO	115	120	0.94	195	198	1.53
CH_4	486	293	2.29	558	323	2.50
TUHC (as C_3H_8)	591	960	7.51	689	1,100	8.51
Particulate mass emissions:						
Solid	-	12.5	0.0978	-	16.2	0.125
Condensable	-	7.3	0.057	-	7.5	0.058
Total	-	19.8	0.155	-	23.7	0.183

[a] NO_x control by increased air-fuel ratio and manifold air cooling.
[b] Appendix A discusses continuous monitor analyzers used, calibration gases and sample gas conditioning system.
[c] Corrected to 15 percent O_2, dry.
[d] Heat input basis.
[e] Shaft output basis.
[f] Also corrected for standard atmospheric conditions of 302K (85°F) dry bulb combustion air temperature at inlet of turbocharger and 10.71 kg H_2O/kg air (75 grains H_2O/lb air) humidity. Emission rates (ng/J, g/Bhp-hr) as NO_2.

elements and organic species. Because of the more isokinetic nature and the stack traversing procedures used with the HVSS (Method 5), particulate mass loadings by this method are considered more accurate than results obtained with the single point SASS sample. Equipment and sampling procedures used for emissions measurement are described in Appendix A.

Total NO_x emissions at baseline averaged 1,040 ppm as measured or 729 ppm corrected to 15 percent oxygen and standard atmospheric conditions (9.87 g/Bhp-hr as NO_2). Increasing air-fuel ratio by 11 percent over baseline conditions with increased manifold air cooling reduced NO_x 42 percent to 510 ppm as measured or 423 ppm (5.06 g/Bhp-hr as NO_2) corrected to 15 percent oxygen and standard atmospheric conditions. The effect of NO_x control on other criteria pollutant emissions was an overall increase in hydrocarbons, CO, and particulate emissions. Total unburned hydrocarbons (TUHC) increased 16 percent, CH_4 increased 15 percent, and CO increased 70 percent (all on a ppm at 15 percent O_2 basis). Particulate emissions increased 20 percent (on a ng/J heat input basis). The increase in air-fuel ratio from baseline conditions resulted in lower peak cylinder temperatures, probably leading to an increase in combustible emissions. Exhaust gas temperature decreased by 35K (63°F) during the low-NO_x test, indicative of increased engine efficiency at constant power output.

Smoke emissions, measured with a Bosch photo-electric meter, showed essentially no smoke under both baseline and low-NO_x operation. Total particulate emissions, measured with the HVSS, increased 20 percent from baseline levels. The increase may be attributed primarily to increases in nonvolatile organic compound emissions collected in the sampling probe and on the filter (solid particulate). A more detailed discussion of the potential

effect of nonvolatile organics on particulate emissions is presented in Section 3.4. Condensable particulate matter that collected in the impinger section of the HVSS, also showed a 3 percent increase during the low-NO_x test.

Solid particulate emissions were also measured with the SASS. For the baseline test, SASS-collected particulate was only 1.33 ng/J (0.0104 g/Bhp-hr), compared to 12.5 ng/J (0.0978 g/Bhp-hr) for the HVSS. For the low-NO_x test, SASS particulate was 6.65 ng/J (0.0515 g/Bhp-hr), compared to 16.2 ng/J (0.125 g/Bhp-hr) for the HVSS test. These differences in particulate emissions measured with the HVSS and SASS may be explained in some part by the contribution of condensation of unburned hydrocarbons in the HVSS, since this equipment operates at lower temperatures than SASS, as well as by the fact that SASS sampling takes place at a single sampling point.

3.3 TRACE ELEMENT EMISSIONS RESULTS

A lube oil sample from the engine and the SASS train samples from the engine exhaust were analyzed for 73 trace elements using Spark Source Mass Spectrometry (SSMS) and Atomic Absorption Spectroscopy (AAS) analysis in accordance with EPA Level 1 analysis protocol (Reference 3-2). Once the trace element concentrations were determined by laboratory analysis, trace element flowrates for lube oil and flue gas vapor and condensed phases could be computed. Trace element concentrations and flowrates are presented in Appendix B.

Table 3-3 summarizes the calculated trace element flowrates for those elements detected in any sample corresponding to both lube oil consumption and exhaust gas under baseline and low-NO_x operation. The lube oil data, calculated based on lube oil analysis and the engine manufacturer's estimate

TABLE 3-3. TRACE ELEMENT FLOWRATES

Element	Lube oil (μg/s)	Engine exhaust (μg/s)	
		Baseline	Low-NO_x
Aluminum	>15	U[a]	44
Antimony	--[b]	0.18	<0.30
Arsenic	<0.080	<1.1	<1.1
Barium	0.40	14	11
Boron	0.16	--	10
Bromine	0.12	4.1	9.5
Cadmium	<0.028	<0.014	<0.014
Calcium	>40	1,300	650
Cerium	--	0.364	11
Cesium	--	0.364	<0.22
Chlorine	5.2	18	180
Chromium	3.6	47	190
Cobalt	0.24	--	65
Copper	1.2	550	650
Fluorine	1.2	372	46
Gallium	--	1.6	6.2
Germanium	--	0.21	<0.22
Iodine	0.080	0.55	0.20
Iron	12	--	3,900
Lanthanum	--	--	8.1
Lead	0.40	42	26
Lithium	0.080	0.014	0.68
Magnesium	>40	21	40
Manganese	0.24	1.8	130
Mercury	<0.040	<1.3	<1.4
Molybdenum	0.32	61	6.6
Neodymium	--	--	1.1
Nickel	0.40	49	4.6
Niobium	--	1.5	0.41
Phosphorus	>40	24	220
Potassium	19	1,700	>2,400
Rubidium	0.028	1.1	0.41
Scandium	<0.016	<0.18	<0.20
Selenium	--[a]	130	81
Silicon	17	730	810
Silver	--	3.6	16

[a]U = Unable to determine.
[b]Dashes indicate that emissions were below the detectable level.

TABLE 3-3. CONCLUDED

Element	Lube oil (μg/s)	Engine exhaust (μg/s)	
		Baseline	Low-NO_x
Sodium	>39	>1,700	>1,900
Strontium	0.80	9.0	3.3
Sulfur	>40	>2,000	>2,200
Tantalum	--	--	<2.2
Tellurium	--	3.6	1.4
Tin	0.36	1.8	0.68
Titanium	3.6	--	44
Vanadium	0.024	0.55	2.4
Yttrium	--	<0.18	<0.20
Zinc	>40	360	460
Zirconium	--	<0.18	0.61

[a]Dashes indicate that emissions were below the detectable level.

of lube oil consumption, represent the only inorganic matter entering the engine, since natural gas is essentially free of inorganic matter. Although the fact that lube oil is consumed does not necessarily indicate that all the trace element content in the oil will be emitted with the engine exhaust or that these represent all of the inorganic matter emitted from the engine, the analysis was performed to estimate the contribution of the lube oil to total inorganic matter. As indicated in Table 3-3, trace elements accounted for by the lube oil generally constitute only an insignificant portion of actual emissions. High trace element emissions may also be caused by the following four factors:

- Exhaust muffler wear
- Engine wear
- Contamination from sampling equipment
- Contamination from analytical procedures

The SASS samples were taken downstream of the engine exhaust muffler. This muffler, which had visibly undergone numerous hours of operation, may actually be the major cause of many of the inorganic element emissions measured during this program. Since muffler related emissions are not directly attributable to engine emissions, further test programs aimed at measuring inorganic emissions from large bore ICE's should take this factor into consideration. The contribution of engine wear may also be a significant cause of many of the trace elements emitted, contributing to the disparity of data between lube oil consumption and engine outlet emission rates shown in Table 3-3. Emissions of iron, copper, nickel, chromium, lead, zinc, and aluminum may have been significantly affected by wear of pistons,

rings, cylinder liners, air blower parts, and other parts exposed to friction and erosion.

The other two factors affecting trace element emissions have to do with contamination of samples inherent to the sampling and analytical procedures. Potential contamination sources during sampling are stainless steel sampling train parts, and tubing used in the SASS train. During analysis, Parr bombing of XAD-2 samples prior to SSMS analysis can introduce contamination for a number of elements, including iron, copper, nickel, chromium, phosphorus, silicon, platinum, and cobalt. Overall, the contribution of contaminants to most of the high concentration elements reported here may be as significant as the contribution from both the muffler and engine wear.

3.4 ORGANIC EMISSIONS RESULTS

Organic emissions during both baseline and low-NO_x tests were measured using four methods. Continuous flame ionization detector (FID) analyses were performed to determine TUHC and methane (CH_4) emissions. FID results are presented in Section 3.2. Further, in accordance with EPA Level 1 analysis protocol (Reference 3-2), volatile organic gas species having boiling points in the C_1 to C_6 range (113 to 373K (-256° to 212°F)) were determined by analyses of exhaust gas samples by gas chromatography. Volatile organic species with boiling points in the C_7 to C_{16} range (373 to 573K (212° to 572°F)) were determined in the laboratory by total chromatographable organic (TCO) analysis of organic module sorbent and condensate extract samples from the SASS train. SASS train samples were also subjected to gravimetric analyses to measure nonvolatile organic species (>C_{16}) having boiling points of >573K (572°F). Further analyses identified organic functional groups and specified particular organic compounds using Infrared Spectrometry (IR) and

gas chromatography/mass spectrometry (GC/MS) analyses, respectively. A discussion of the analytical results follows.

3.4.1 C_1 to C_6, TCO, and Gravimetric Analyses

Table 3-4 summarizes organic emission results from the C_1 to C_6, TCO, and gravimetric analyses. In general, it is difficult to draw firm conclusions from these data regarding the effect of low-NO_x operation on total organic emissions because of measurement problems experienced during the test program. Volatile organic (C_1 to C_6) samples, normally analyzed in the field, were collected from the engine and shipped in sealed glass bulbs to the laboratory for analysis because of a malfunction of the onsite Carle GC analyzer. As indicated in Table 3-4, the baseline sample showed the absence of C_1 to C_4 gases, while these were detected at significant levels in the low-NO_x test sample. C_5 and C_6 hydrocarbons were not detected in either the baseline or low-NO_x test.

Based on the continuous hydrocarbon monitor data as well as volatile organic emission results from the low-NO_x test sample, the absence of C_1 to C_4 hydrocarbons in the baseline sample suggests that a loss of the sample occurred during shipping. In fact, the GC C_1 to C_6 results for both the baseline and low-NO_x tests are suspect, based on the total unburned hydrocarbon data from the continuous monitor shown in Table 3-2. By converting total unburned hydrocarbon emissions obtained with continuous monitors from ppm to mg/dscm and comparing it to the GC results, approximately 25 percent loss of sample in the glass bulbs transported for GC analysis of C_1 to C_6 volatile organics for the low-NO_x test is also suspected. A total loss of sample apparently occurred for the baseline test.

TABLE 3-4. SUMMARY OF TOTAL ORGANIC EMISSIONS FROM SPARK-IGNITED ENGINE (mg/dscm)

Organic emissions	Baseline test	Low-NO_x test
Volatile organic gases analyzed by gas chromatography		
C_1	ND[a]	408
C_2	ND	50.9
C_3	ND	6.3
C_4	ND	11.4
C_5	ND	ND
C_6	ND	ND
Total C_1 to C_6	[b]	476
Volatile organic materials analyzed by TCO procedure		
XAD-2 extract	2.1	2.4
Organic module condensate	0.045	0.055
Total TCO	2.1	2.5
Nonvolatile organic materials analyzed by gravimetric procedure		
Filter + probe catch	<0.12	2.0
XAD-2 cartridge	57	19
Organic module condensate	1.2	0.60
Total Grav	58	22
Total Organics	[b]	498

[a]ND = Not detected.
[b]Sample loss suspected based on hydrocarbon emission data by continuous monitors and results from the low-NO_x test.

Emission levels of total chromatographable organics with boiling points in the C_7 to C_{16} range (373 to 573K (212° to 572°F)), were approximately the same for both tests. However, higher molecular weight organics, (i.e., $>C_{16}$) showed about a 60 percent decrease. These data, combined with continuous hydrocarbon monitor data presented in Table 3-2, indicate that the increase in air-fuel ratio and lower manifold combustion air temperature have the effect of increasing emissions of low molecular weight volatile organics but result in little change or even a decrease in emissions of semi- and nonvolatile organic compounds.

Figures 3-1(a) and 3-1(b) illustrate organic and particulate emission results for both the baseline and low-NO$_x$ tests in terms of the measurement temperature of the particulate samples and the boiling points of organic compounds collected. For the baseline test, Figure 3-1(a), the loss of sample for C_1 to C_6 vapor hydrocarbon is indicated. Figure 3-1(a) shows that the organic matter in the probe and filter catch of the SASS accounts for 6 percent of the total particulate weight collected (0.077 ng/J organics from 1.2 ng/J total weight). The figure also shows that 35 ng/J of gravimetric organics and 1.3 ng/J of TCO organics were accounted for in the XAD-2 extract and organic module condensate.

The presence of organic matter in quantities amounting to a mass emission rate greater than that corresponding to the particulate matter collected in the Method 5 train may have, in fact, contributed to the larger particulate emissions measured with Method 5. Because the probe and filter catches of the Method 5 train are not analyzed for organic content, the contribution of organics condensing in the temperature range of 363 to 573K (193° to 572°F) to the total weight catch cannot be computed. However,

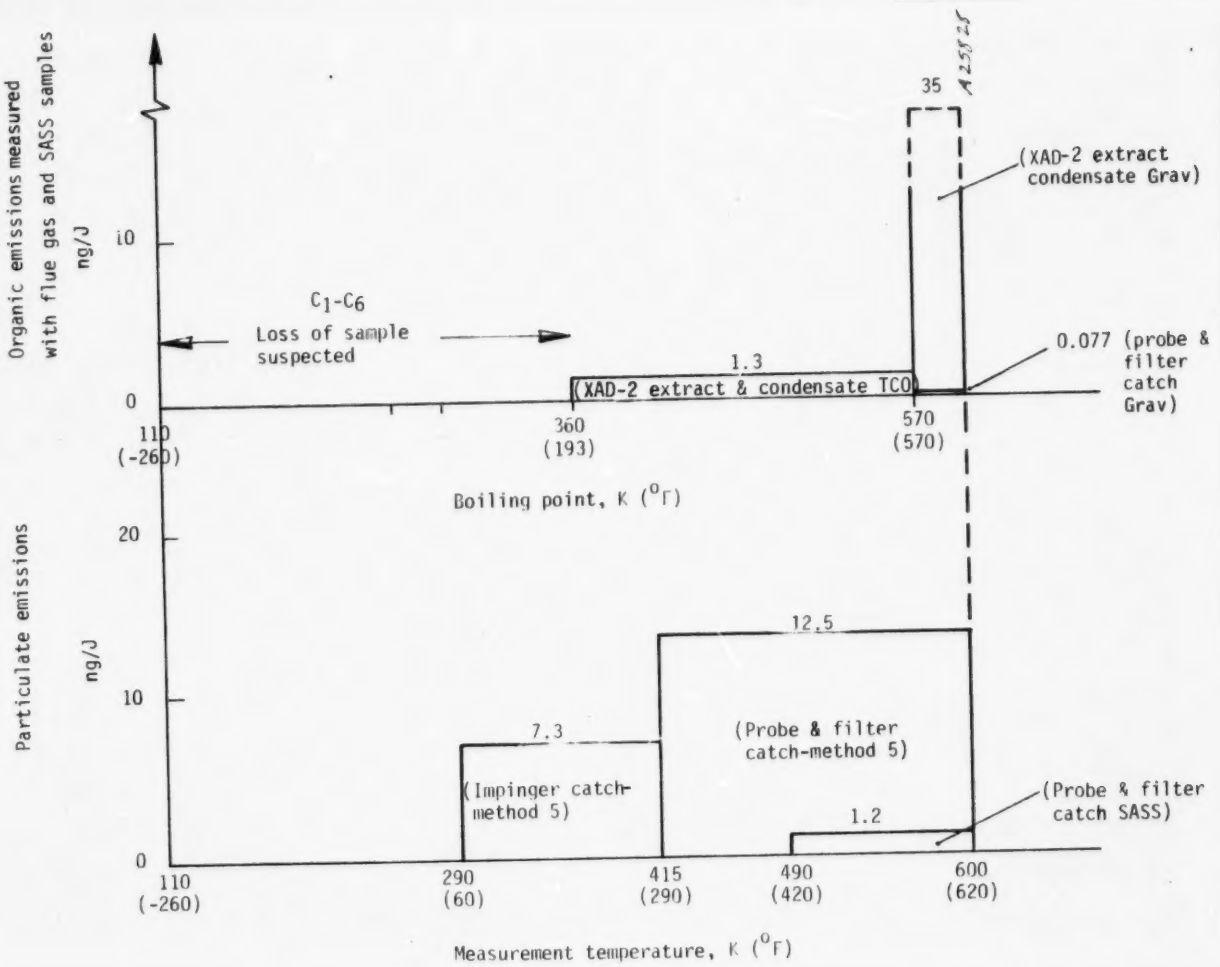


Figure 3-1(a). Summary of organic and particulate emission results ng/J -- baseline test.

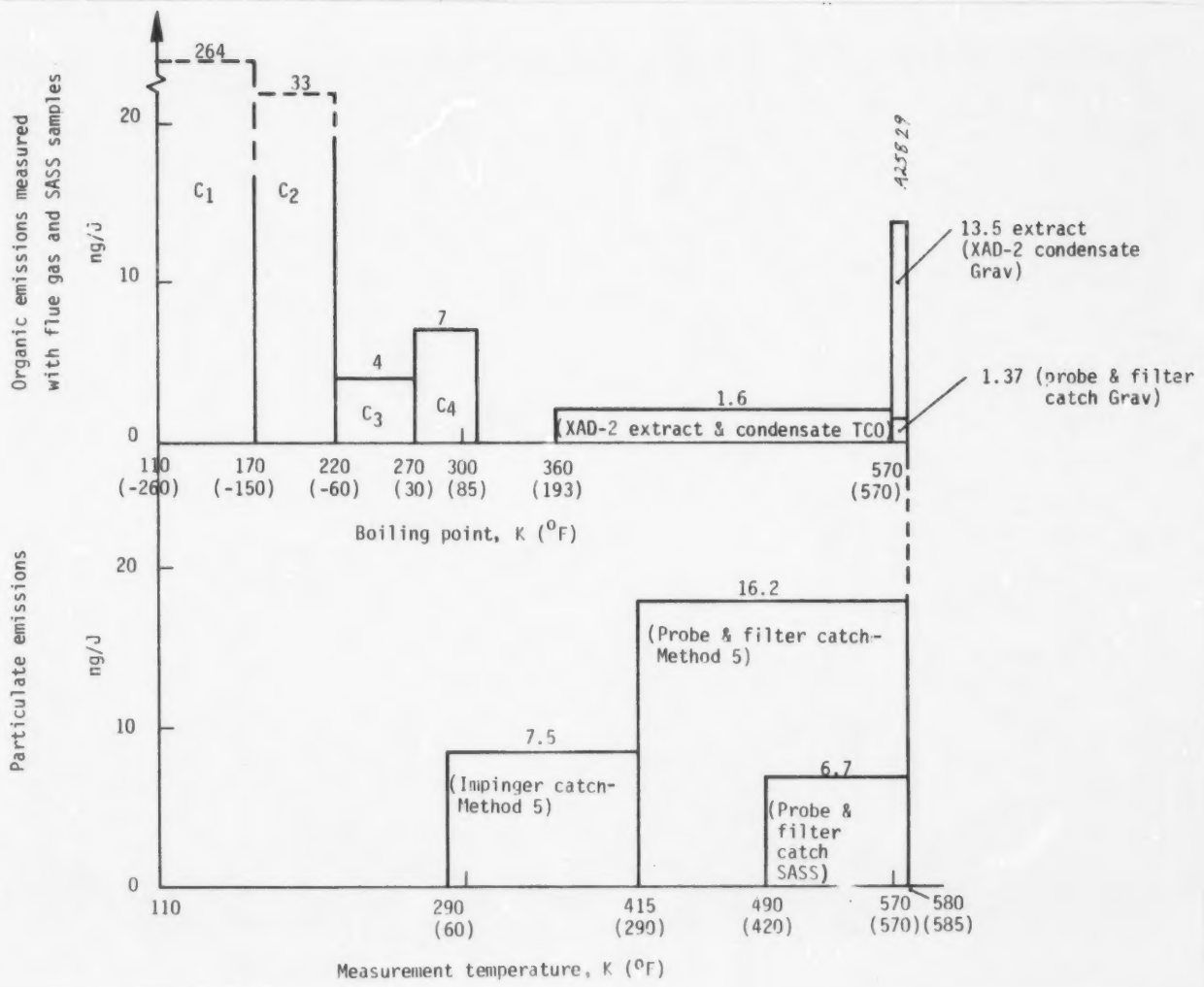


Figure 3-1(b). Summary of organic and particulate emission results ng/J -- low-NO_x test

because Method 5 samples are collected at lower temperature than SASS particulate samples, it is possible that larger quantities of these organic compounds may have condensed on the probe and the filter of the Method 5 train than on the probe and filter of the SASS, accounting, in part, for the disparity of particulate emission data between the two methods.

Figure 3-1(b) illustrates similar results for the low-NO_x test. Here, emissions of C_1 to C_4 are indicated. Because of their low boiling points, these compounds do not condense in particulate matter in either the Method 5 or SASS samples. Analysis of the SASS probe and filter catch indicates that organic matter for this test accounts for 20 percent of the total SASS particulate catch (1.37 ng/J organics, 6.7 ng/J total particulate catch). As in the case with the baseline test, the solid particulate emissions measured from the probe and filter catches of the Method 5 train are significantly higher than that of the SASS train. Again, greater condensation of organics in the probe and filter of the Method 5 train may have occurred because of the lower measurement temperature compared with the SASS.

3.4.2 Infrared Spectra of Total Extracts

IR spectrometry was used to identify organic functional groups present in SASS samples. The results of the IR analyses for the total extract samples are summarized in Table 3-5. The spectra of the XAD-2 extracts and the organic module condensate extracts for both tests were quite similar. However, the baseline test filter extract spectrum was significantly weaker than the low-NO_x test filter extract spectrum. The spectra suggested the presence of aliphatic hydrocarbons as primary constituents in all samples collected by SASS in both the baseline and low-NO_x tests. Absorbances characteristic of carboxylic acid were also found in all samples, although

TABLE 3-5. SUMMARY OF INFRARED SPECTRA OF TOTAL SAMPLE EXTRACTS

Sample	Baseline test				Low-NO_x test			
	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present
Filter	No peaks	--	--	--	3,575 to 3,075	W	O-H	Aliphatic hydrocarbons, some carboxylic acids
					2,905	S	C-H	
					2,848	S	C-H	
					2,750 to 2,450	W	O-H	
					1,725	M	C=O	
					1,445	M	C-H	
					1,375	W	C-H	
XAD-2 Extract	3,575 to 3,075	W	O-H	Alkanes, alkenes, some carboxylic acids and other oxygenates, and nitrites	3,575 to 3,075	W	O-H	Alkanes, alkenes, some carboxylic acids and other oxygenates, and nitrates
	2,905	S	C-H		2,905	S	C-H	
	2,845	S	C-H		2,845	S	C-H	
	2,750 to 2,450	W	O-H		2,750 to 2,450	W	O-H	
	1,725	M	C=O		1,725	M	C=O	
	1,635	W	C=C		1,635	W	C=C	
	1,550	W	Nitrate		1,550	W	Nitrate	
	1,445	W	C-H		1,445	W	C-H	
	1,375	W	C-H/nitrate		1,325	W	C-H/nitrate	
	1,265	W	C-O		725	W	C=C	
Organic module condensate extract	3,580 to 2,980	W	O-H	Aliphatic hydrocarbons and some carboxylic acids	3,580 to 2,980	W	O-H	Aliphatic hydrocarbons and some carboxylic acids
	2,905	S	C-H		2,905	S	C-H	
	2,845	S	C-H		2,845	S	C-H	
	2,250 to 2,450	W	O-H		2,750 to 2,450	W	O-H	
	1,670	S	C=O		1,680	M	C=O	
	1,445	W	C-H					

[a]W = weak
M = moderate
S = strong

these were weaker, suggesting that such compounds were present at lower concentrations than the aliphatic hydrocarbons. Both XAD-2 extracts contained absorbances characteristic of alkyl nitrates, but at low concentrations.

3.4.3 Gas Chromatography/Mass Spectrometry Analysis for POM and Other Organic Compounds

Identification of specific organic compounds (the semivolatile organic priority pollutant compounds) including several polycyclic organic matter (POM) species, was performed by GC/MS analysis total sample extracts. Table 3-6 lists the compounds sought in the GC/MS analyses and their detection limits. Table 3-7 presents the compounds which were detected and their respective emission levels. As indicated, only two POM isomer pairs were found in both the baseline and low-NO_x tests. The bis(2-ethylhexyl)-phthalate levels noted are probably a result of contamination during sampling or laboratory analysis.

POM species with known carcinogenic properties such as benzo(a)pyrene and dibenz(a,h)anthracene were not detected. The detection limits of the GC/MS analysis for these two compounds were 0.3 and 1.8 μg/dscm, respectively.

3.4.4 Liquid Chromatography of Selected Sample Extracts

The XAD-2 sample extracts for both tests and the SASS particulate extract for the low-NO_x test were separated via liquid chromatography (LC) fractionation since these extracts contained greater than 15 mg of total organic. The GRAV and TCO contents were then obtained for each LC fraction. Results of these analyses are given in Tables 3-8 to 3-10. For the baseline test, almost half the organic material in the XAD-2 extract was found in the

TABLE 3-6. COMPOUNDS SOUGHT IN GC/MS ANALYSIS AND THEIR DETECTION LIMITS (ng/μl injected)

8[a]	4-bromophenyl phenyl ether	40[a]	indeno(1,2,3-cd)pyrene
1[a]	bis(2-chloroisopropyl)ether	2[a]	pyrene
2[a]	bis(2-chloroethoxy)methane	2[a]	acenaphthene
8[a]	hexachlorobutadiene	100[a]	benzidine
40[a]	hexachlorocyclopentadiene	8[a]	1,2,4-trichlorobenzene
1[a]	isophorone	8[a]	hexachlorobenzene
1[a]	naphthalene	8[a]	hexachloroethane
8[a]	nitrobenzene	3[a]	bis(2-chloroethyl)ether
4[a]	N-nitrosodiphenylamine	2[a]	2-chloronaphthalene
40[a]	N-nitrosodi-n-propylamine	4[a]	1,2-dichlorobenzene
3[a]	bis(2-ethylhexyl)phthalate	8[a]	1,3-dichlorobenzene
3[a]	butyl benzyl phthalate	4[a]	1,4-dichlorobenzene
1[a]	di-n-butyl phthalate	20[a]	3,3-dichlorobenzidine
2[a]	di-n-octyl phthalate	10[a]	2,4-dinitrotoluene
2[a]	diethyl phthalate	10[a]	2,6-dinitrotoluene
2[a]	dimethyl phthalate	1[a]	1,2-diphenylhydrazine (as azobenzene)
5[a]	benz(a)anthracene	2[a]	fluoranthene
7[a]	benzo(a)pyrene	4[a]	4-chlorophenyl phenyl ether
8[a]	3,4-benzofluoranthene	40	anthanthrene
8[a]	benzo(k)fluoranthene	40	benzo(e)pyrene
5[a]	chrysene	--[b]	dibenzo(a,h)pyrene
1[a]	acenaphthylene	--[b]	dibenzo(a,i)pyrene
1[a]	anthracene	40	dibenzo(c,g)carbozole
40[a]	benzo(ghi)perylene	40	7,12 dimethyl benz(a)anthracene
2[a]	fluorene	40	3-methyl cholanthrene
1[a]	phenanthrene	40	perylene
40[a]	dibenz(a,h)anthracene	40	benzo(c)phenanthrene

[a]Authentic standard run
[b]Molecular weight too high for direct analysis by base/neutral run

TABLE 3-7. POM EMISSION SUMMARY FOR SPARK IGNITED ENGINE (μg/dscm)

Compound	Baseline test	Low-NO_x test
Bis(2-ethylhexyl)phthalate	1,130	<8
Chrysene/Benz(a)anthracene	4	<2
Phenanthrene/Anthracene	4	3

TABLE 3-8. TCO AND GRAV RESULTS FOR COLUMN CHROMATOGRAPHY OF THE BASELINE TEST XAD-2 EXTRACT

			Total	
Fraction	TCO (mg/dscm)	GRAV (mg/dscm)	(mg/dscm)	(ng/J heat input)
LC 1	0.40	4.8	5.2	3.2
LC 2	0.40	<0.4	0.40	0.25
LC 3	0.14	1.6	1.7	1.0
LC 4	0.04	0.60	0.64	0.39
LC 5	<0.004	0.96	0.96	0.59
LC 6	0.02	1.2	1.2	0.74
LC 7	<0.004	0.84	0.84	0.52
Total	1.0	10	11	6.8

TABLE 3-9. TCO AND GRAV RESULTS FOR COLUMN CHROMATOGRAPHY OF THE LOW-NO_x TEST FILTER EXTRACT

Fraction	TCO[a] (mg/dscm)	GRAV (mg/dscm)	Total (mg/dscm)	Total (ng/J heat input)
LC 1	--	0.76	0.76	0.53
LC 2	--	0.08	0.08	0.06
LC 3	--	0.3	0.3	0.21
LC 4	--	0.1	0.1	0.07
LC 5	--	0.1	0.1	0.07
LC 6	--	0.3	0.3	0.21
LC 7	--	0.1	0.1	0.07
Total	--	1.7	1.7	1.2

[a]TCO not required, sample collected at high temperature.

TABLE 3-10. TCO AND GRAV RESULTS FOR COLUMN CHROMATOGRAPHY OF THE LOW-NO_x TEST XAD-2 EXTRACT

Fraction	TCO (mg/dscm)	GRAV (mg/dscm)	Total (mg/dscm)	Total (ng/J heat input)
LC 1	0.72	<0.23	0.72	0.50
LC 2	0.04	0.79	0.83	0.57
LC 3	0.11	1.1	1.2	0.83
LC 4	0.02	0.74	0.76	0.53
LC 5	<0.001	0.53	0.53	0.37
LC 6	<0.001	1.6	1.6	1.1
LC 7	<0.001	0.80	0.80	0.55
Total	0.89	5.5	6.4	4.4

first LC fraction, the rest being relatively evenly distributed through the rest of the fractions. Fraction 1 generally contains aliphatic hydrocarbons.

For the low-NO_x test the elution pattern in the particulate extract and the XAD-2 extract were different. For the particulate extract, almost half the organic material was again in the first fraction, but the bulk of the remainder was found in fractions 3 and 6. Fraction 3 contains aromatic compounds and fused ring aromatics while fraction 6 generally contains carboxylic acids and esters, alcohols, ketones, and phenols (polar oxygenates). The material in the XAD-2 extract fractionation was fairly evenly distributed among all seven fractions. With the exception of fraction 1, the concentration of the XAD-2 extract organics was approximately the same in both tests. The baseline test extract had a higher level in fraction 1 than did the low-NO_x test extract. Total organics were about 50 percent higher in the baseline test than in the low-NO_x test.

3.4.5 IR Spectra of LC Fractions

The GRAV residues of all sample fractions obtained from LC fractionation of the extracts were subjected to IR spectrometry analysis. Table 3-11 summarizes the IR spectra results for the XAD-2 extracts. Only fraction 1 of the baseline test and fractions 1, 3 and 5 of the low-NO_x test had spectra strong enough to interpret. The presence of aliphatic hydrocarbons is suggested by the LC 1 spectra of both tests. Only the presence of hydrocarbons can be inferred in the low-NO_x test LC 3 and LC 5 spectra.

TABLE 3-11. SUMMARY OF IR SPECTRA FOR LC FRACTIONS OF XAD-2 EXTRACTS

	Baseline test				Low NO_x test			
Fraction	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present
LC 1	2,920	S	C-H	Aliphatic hydrocarbons	2,920 2,840 1,640 1,440 1,370	S S W M M	C-H C-H C=C C-H C-H	Aliphatic hydrocarbons
LC 2	No peaks	--	--	--	No peaks	--	--	--
LC 3	No peaks	--	--	--	2,920 2,840	S S	C-H C-H	Hydrocarbons
LC 4	No peaks	--	--	--	No peaks	--	--	--
LC 5	No peaks	--	--	--	2,920	S	C-H	Hydrocarbons
LC 6	No peaks	--	--	--	No peaks	--	--	--
LC 7	No peaks	--	--	--	No peaks	--	--	--

[a] W = weak
M = moderate
S = strong

Table 3-12 summarizes the IR spectra of the low-NO_x test particulate extract LC fractions. Only the spectra for LC fractions 1 through 4 were sufficiently strong to be interpreted, and only the presence of hydrocarbons could be inferred from the spectra.

Comparing the LC fraction spectra in Tables 3-11 and 3-12 with the total extract spectra summarized in Table 3-5 shows that all absorbances found in the LC fractions of a given sample were present in the total sample. However, some bands were seen in the total extract that were not seen in the fractions. The low recovery of the XAD-2 extract fractionation (20 and 30 percent) no doubt contributes to this.

3.4.6 Low Resolution Mass Spectrometry Analysis of LC Fractions

Several LC fractions of the XAD-2 extracts from both the baseline test and the low-NO_x test and the several combined LC fractions of the filter extract from the low-NO_x test had concentrations of organics in excess of 0.5 mg/dscm. Thus, they were subjected to low resolution mass spectrometry (LRMS) analysis. Table 3-13 presents the results of these analyses.

As shown in the table, the material of significance was indicated to be aliphatic hydrocarbons. Some phenolics were seen in LC 5 of the baseline XAD-2 extract and LC 6 of the low-NO_x extract, and some carboxylic acids were identified in LC 7 of the low-NO_x XAD-2 extract. Low molecular weight polynuclear aromatics (naphthalene and alkyl naphthalenes) were identified in LC 1 of the low-NO_x XAD-2 extract.

TABLE 3-12. SUMMARY OF THE IR SPECTRA FOR LC FRACTIONS OF THE LOW-NO_x TEST PARTICULATE EXTRACT

Fraction	Frequency (cm^{-1})	Intensity[a]	Possible assignment	Possible compound categories present
LC 1	2,920	S	C-H	Aliphatic hydrocarbons
	2,860	S	C-H	
LC 2	2,920	S	C-H	Aliphatic hydrocarbons
	2,840	S	C-H	
LC 3	2,920	S	C-H	Hydrocarbons
LC 4	2,920	S	C-H	Hydrocarbons
	2,840	S	C-H	
LC 5	No peaks	--	--	--
LC 6	No peaks	--	--	--
LC 7	No peaks	--	--	--

[a]S = strong

TABLE 3-13. SUMMARY OF LRMS ANALYSES

Test/Sample	Fraction[a]	Compound category	Intensity[b]
Baseline			
XAD-2 extract	1	Aliphatic hydrocarbons, MW < 216	1
	5	Phenols	10
Low-NO_x			
Filter extract	1	Aliphatic hydrocarbons	1
XAD-2 extract	1	Fused alternate/nonalternate hydrocarbons, MW 128 to 141 (naphthalene plus alkyls)	100
		Alphatic hydrocarbons, MW <216	100
		Aromatic hydrocarbons	10
	6	Phenols	10
	7	Carboxylic acids	10
		Phenols	1

[a]No compound categories identified in sample fractions other than those noted.
[b]100: Major component, 10: Minor component, 1: Trace component.

REFERENCE FOR SECTION 3

3-1. "DEMA Exhaust Emission Measurement Procedure for Low and Medium Speed Internal Combustion Engines," Diesel Engine Manufacturers Association, Cleveland, Ohio, 1974.

3-2. Lentzen, D. E., et al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB293795, October 1978.

SECTION 4

ENVIRONMENTAL ASSESSMENT

This section discusses the potential environmental impact of the engine tested and also discusses the results of the bioassay testing of the exhaust gas samples collected from the engine. The potential environmental impact is evaluated by comparing exhaust gas stream species concentrations to occupational exposure guidelines. These comparisons are made to rank species discharged for possible further consideration. Bioassay analyses were conducted as a more direct measure of the potential health and ecological effect of the effluent streams. Both these analyses are aimed at identifying potential problem areas and providing the basis for ranking pollutant species and discharge streams for further consideration.

4.1 EMISSIONS ASSESSMENT

To obtain a measure of the potential significance of the discharge streams analyzed in this test program, discharge stream concentrations were compared to indices which reflect potential for adverse health effects. For the exhaust gas discharge, the indices used for comparison were occupational exposure guidelines, generally either the time-weighted-average Threshold Limit Values (TLV's) defined by the American Conference of Governmental Industrial Hygienists (ACGIH) (Reference 4-1), or the 8-hr time-weighted average exposure limits established by the Occupational Safety and Health Administration (OSHA) (Reference 4-2).

The comparisons of the exhaust gas stream species concentrations to these occupational exposure guidelines were only performed to rank species emission levels with respect to potential for adverse effects. Conclusions concerning absolute risk associated with emissions are not, and should not, be drawn. These evaluations are only presented to place different species emitted into perspective and to rank them for further consideration.

Table 4-1 lists those pollutant species emitted in the exhaust gas at levels greater than 10 percent of their occupational exposure guideline. As noted in the table, several trace elements were emitted at levels up to three times their occupational exposure guidelines. However, as noted in Section 3.3, trace elements measured in the exhaust gas may be attributable to wear of internal parts of the muffler and the engine and to contamination introduced in the sampling/analysis procedures, although confirmation is not possible with the available data. For comparison, emissions of the gaseous criteria pollutant CO were at levels 4 to 5 times greater than its occupational exposure guideline; NO_x emissions were at levels several hundred times its occupational exposure guideline. With respect to potential environmental impact, the greatest effect of NO_x control was the reduction in NO_x emissions, based on comparison of exhaust emission levels to occupational exposure guidelines.

4.2 BIOASSAY RESULTS

Bioassay tests were performed on the organic sorbent (XAD-2) extracts. The bioassay tests performed on the XAD-2 extracts were health effects tests only (Reference 4-3). These were:

- Ames assay, based on the property of Salmonella typhimurium mutants to revert due to exposure to various classes of mutagens

TABLE 4-1. EXHAUST GAS POLLUTANTS EMITTED AT CONCENTRATIONS EXCEEDING 0.1 OF THEIR OCCUPATIONAL EXPOSURE LIMIT

Pollutant	Exhaust Gas Concentration (mg/dscm)		Occupational Exposure Guideline (mg/m^3)[a]
	Baseline	Low NO_x	
NO_x (as NO_2)	1,990	976	6.0
CO	198	295	55
Copper, Cu	0.25	0.27	0.10[b]
Iron, Fe	--	1.6	1.0
Chromium, Cr	0.022	0.079	0.050
Phosphorus, P	0.011	0.090	0.10
Silver, Ag	0.0017	0.0068	0.010
Potassium, K	>0.80	>0.98	2.0[c]
Sodium, Na	>0.80	>0.80	2.0[c]
Lead, Pb	0.020	0.011	0.050[b]
Calcium, Ca	0.59	0.27	2.0
Selenium, Se	0.059	0.034	0.20
Cobalt, Co	--	0.027	0.10
Nickel, Ni	0.023	0.0019	0.10

[a]Time-weighted average Threshold Limit Value (Reference 4-1), unless noted.
[b]8-hr time-weighted average OSHA exposure limit (Reference 4-2).
[c]Ceiling limit.

- Cytotoxicity assay (CHO) with mammalian cells in culture to measure cellular metabolic impairment and death resulting from exposure to toxicants

A detailed description of the biological analyses for health effects of exhaust gas under baseline and low-NO_x operation is presented in Volume II: Data Supplement. The results of these assays are summarized in Table 4-2 for the exhaust gas samples (organic sorbent module extract) for both baseline and low-NO_x tests. These results suggest that the exhaust gas, under both baseline and low-NO_x operation, is of moderate to high toxicity and mutagenicity.

4.3 SUMMARY

A spark-ignited large bore reciprocating IC engine was tested under baseline (uncontrolled) operation, and with increased air/fuel ratio operation to control NO_x emissions to below the proposed NSPS limit of 700 ppm (at 15 percent O_2). Accordingly, NO_x emissions were decreased 42 percent from 729 to 423 ppm (15 percent O_2). With increased air/fuel ratio engine efficiency increased slightly from 34.3 to 34.7 percent. CO,

TABLE 4-2. BIOASSAY RESULTS -- SPARK-IGNITED ENGINE

		Evaluation	
Sample	Test	CHO[a]	Ames[b]
XAD-2 extract	Baseline	H/M	H
XAD-2 extract	Low-NO_x	H/M	M

[a]H -- High toxicity, M -- moderate toxicity
[b]H -- High mutagenicity, M -- moderate mutagenicity

methane, and total unburned hydrocarbon (as measured by a continuous hydrocarbon analyzer) emissions all increased with NO_x control, CO increased from 115 to 195 ppm methane from 486 to 448 ppm, and TUHC from 591 to 689 ppm (as propane), all corrected to 15 percent O_2. Particulate emissions were relatively constant at about 20 ng/J heat input.

Total semivolatile organic species emissions (nominally C_7 to C_{16} organics) remained constant at 2.1 to 2.5 mg/dscm with NO_x control. However, total nonvolatile organic (nominally C_{16+} organics) emissions decreased from 58 to 22 mg/dscm. Aliphatic hydrocarbons were the predominant compound category comprising the organic emissions. The presence of phenols was apparent in the exhaust gas for both tests. Carboxylic acids and aromatic hydrocarbons were apparent in the low-NO_x test exhaust.

Of the 58 semivolatile organic priority pollutants analyzed, only phenanthrene/anthracene and chrysene/benz(a)anthracene were detected. They were present in the baseline test exhaust at 4 µg/dscm, and at <2 to 3 µg/dscm in the low-NO_x test exhaust.

REFERENCES FOR SECTION 4

4-1. "Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment With Intended Changes for 1983-84," American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1983.

4-2. OSHA Safety and Health Standards, 29 CFR Part 1910, Subpart Z.

4-3. Brusick, D. J., and R. R. Young, "IERL-RTP Procedures Manual: Level 1 Environmental Assessment Biological Tests" EPA-600/8-81-024, NTIS PB228966, October, 1981.

APPENDIX A

SAMPLING AND ANALYSIS METHODS

Emission test equipment was provided by Acurex Corporation and Colt Industries. Continuous monitoring analyses for criteria pollutants and other gas species emissions were provided by Colt Industries. The gas monitoring system is used by the engineering personnal of Colt Industries in studying NO_x controls for reciprocating internal combustion engines and monitoring their effects. Onsite equipment provided by Acurex Corporation included particulate analysis trains (i.e., EPA Method 5 specified equipment), the SASS train, and a gas chromatograph analyzer for volatile hydrocarbon analysis. A laboratory area was provided by Colt Industries for equipment preparation, sample recovery, and preliminary onsite sample analysis.

The following sections briefly describe the equipment and sample procedures used during Level 1 source evaluation and assessment of NO_x control for the reciprocating internal combustion engine at the Fairbanks Morse Division of Colt Industries.

A.1 CONTINUOUS MONITORING SYSTEM FOR GASEOUS EMISSIONS

The continuous monitoring system for gaseous emissions conformed to the DEMA exhaust emission measurement procedure (Reference A-1). The list of analytical equipment and calibration gases used is presented in Table A-1. The exhaust gas sample was taken upstream of the engine exhaust muffler and the heat exchanger which served to control combustion air inlet temperature.

TABLE A-1. LIST OF CONTINUOUS MONITORING ANALYZERS AND CALIBRATION GASES USED

Continuous Monitors

Species	Manufacturer	Measurement Method	Model Number
CO_2/CO	Infrared Industries, Inc. Santa Barbara, California	IR Spectrometer	702
O_2	Serbomax (Scott Corp)	Paramagnetic	150
$NO-NO_x$	Thermo Electron Co.	Chemiluminescent	10A
CH_4/UHC	Scott Corporation	Flame Ionization	215
Smoke	Bosch - W. Germany	Light transmissometer	EFAW 68A

Calibration Gases

Species	Manufacturer	Concentrations	Age
CO/CO_2	Air Co. Specialty Gases	409 ppm CO 5.21% CO_2	2 months
NO/NO_2	Air Co. Specialty Gases	967 ppm NO 8 ppm NO_2	2 months
C_3H_8	Air Co. Specialty Gases	29 ppm and 765 ppm	2 months
O_2 (zero air)	Air Co. Specialty Gases	2.0%	2 months

A heated sample line, equipped with two filters (one inside the exhaust duct and one outside) was used to draw the gas to the total hydrocarbon and methane emission monitoring system. An unheated sample line, connected to the heated line upstream of the hydrocarbon analyzer, served the remaining instruments in the continuous monitoring system.

A Bosch smoke emission analyzer was also used in the test program. This instrument remained in service throughout the test. Figure A-1 illustrates the relationship between the Bosch-0.3 liter and the Bacharach smoke readings. The Bosch smokemeter is used widely among engine manufacturers.

A.2 PARTICULATE TESTS

Particulate mass tests were conducted in accordance with EPA Reference Methods 1 through 5. The following sampling equipment was used:

- A 316 stainless steel sampling nozzle properly sized for isokinetic sampling
- Stainless steel-lined sampling probe equipped with a thermocouple to measure probe temperature, a thermocouple to measure stack gas temperature, and a calibrated S-type pitot tube to measure velocity pressure
- A teflon-coated stainless steel 142 mm (5.59 in.) filter holder
- An impinger train containing four glass bottles to collect moisture and condensible material escaping the filter
- A 4.7×10^{-3} m^3/s (10-cfm) carbon vane pump modified for very low leakage around the shaft
- A control module to monitor temperature, pressure, and flowrate throughout the sampling train

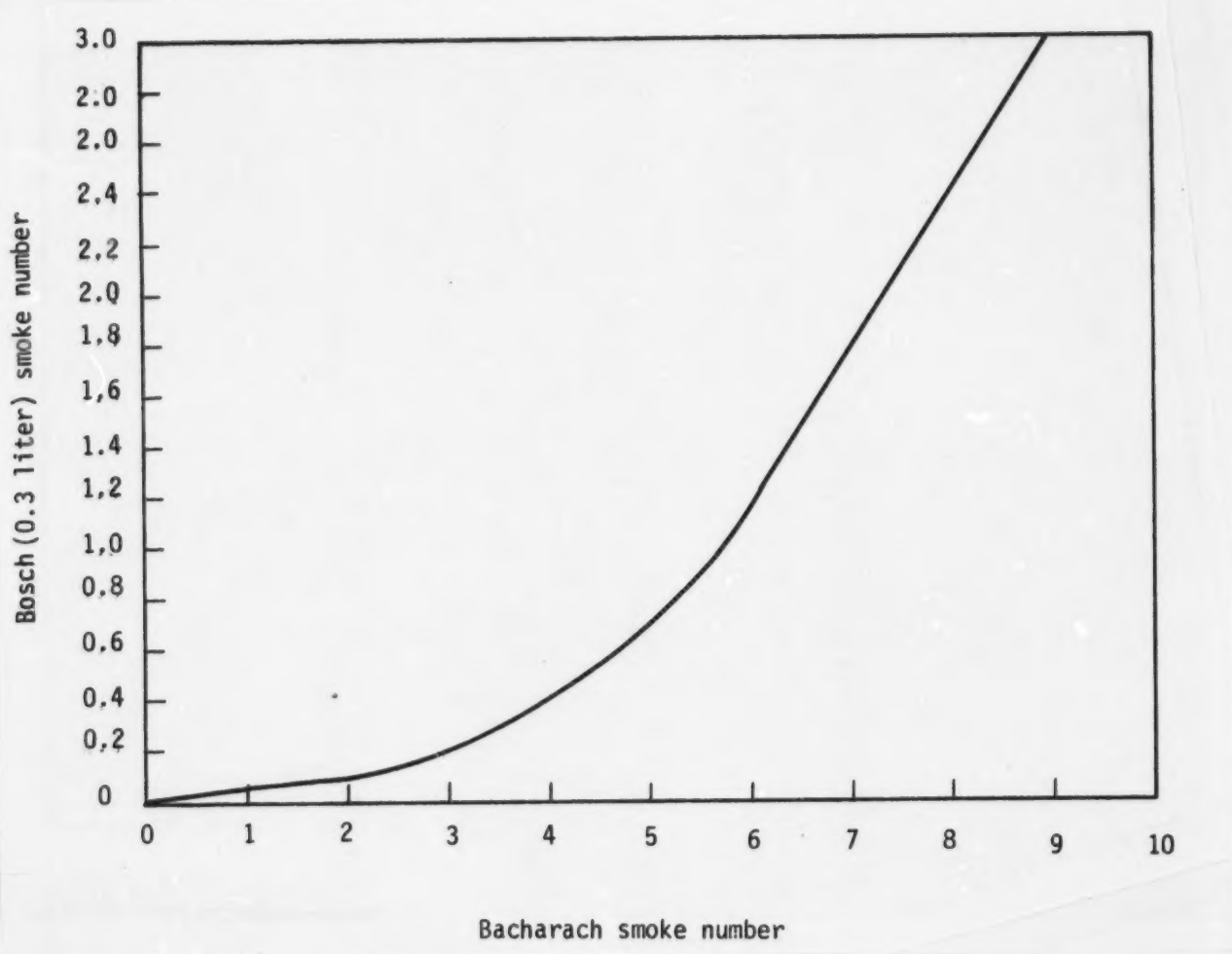


Figure A-1. Relation of Bosch to Bacharach Smoke Numbers.

Sampling Probe

A 1.52m (5-ft) heated stainless steel-lined probe was used to isokinetically extract samples from the stack. The probe has a closed loop temperature control system to keep the probe at 394K (250°F), as required by EPA Method 5. The probe is equipped with an S-type pitot tube to measure stack gas velocity pressure and a thermocouple to measure stack gas temperature.

Filter Holder

For the particulate mass tests, a 316 stainless steel, Teflon-coated 142-mm (5.59-in.) filter holder containing a glass fiber filter was used to capture the particulates.

Impinger Train

The impinger train for the particulate mass tests was immersed in an icebath and consisted of four glass impinger bottles equipped with teflon caps and 316 stainless steel stems, connector tubes, and fittings. The first two bottles contained 400 ml of distilled water, the third bottle was empty, and the fourth contained a known amount of silica gel.

Control Module

The control module monitors temperatures, pressures, and flowrates throughout the sampling train. For these tests, the orifice ΔH is indicated on a 0-1.5 kPa (0 to 6 in. H_2O) magnehelic gauge where the smallest division is 25 Pa (0.1 in. H_2O). The velocity pressure of the stack gases is indicated on a 0 to 124 Pa (0 to 0.5 in. H_2O) or a 0 to 1 kPa (0 to 4 in. H_2O) magnehelic gauge.

The control module contains a Rockwell Model 415 dry gas meter to measure the total volume of gas sampled to the nearest 1.4×10^{-4} m^3

(0.005 ft^3). An orifice meter (after the dry gas meter) is used to measure the instantaneous flowrate through the sampling train to ensure sampling is done isokinetically.

Finally, the control module has an eight-position thermocouple switch to measure temperatures throughout the sampling train. Figure A-2 illustrates all these components of the Acurex High Volume Stack Sampler used for conducting the test program.

A.2.1 Sample Collection

Sample collection took place on the uninsulated stack above the engine exhaust muffler. For each test, clean filters were placed in the sealed filter holder in the cleanup laboratory and transported to the stack for use. Once on the stack the sample train was assembled. Leak checks were performed before and after each test and as necessary during the test. Upon completion of the test, the probe and nozzle were cleaned and the impinger solution volumes were measured and recorded. The filter holder was sealed and brought to the cleanup laboratory for reclaiming.

The particulate tests were performed at 36 sample points in accordance with EPA Method 1. These test points are illustrated in Figure A-3. Each point was sampled for 5 minutes, hence a 180 minute total sample time.

A.2.2 Sample Recovery

Figure A-4 illustrates the Method 5 sample recovery utilized to measure total particulate mass collected with the HVSS train. Solid particulate matter is defined as all particulate mass collected in the front half of the train; that is the filter, the probe, and the nozzle. Condensible particulate matter is obtained from gravimetric analyses of impinger liquids

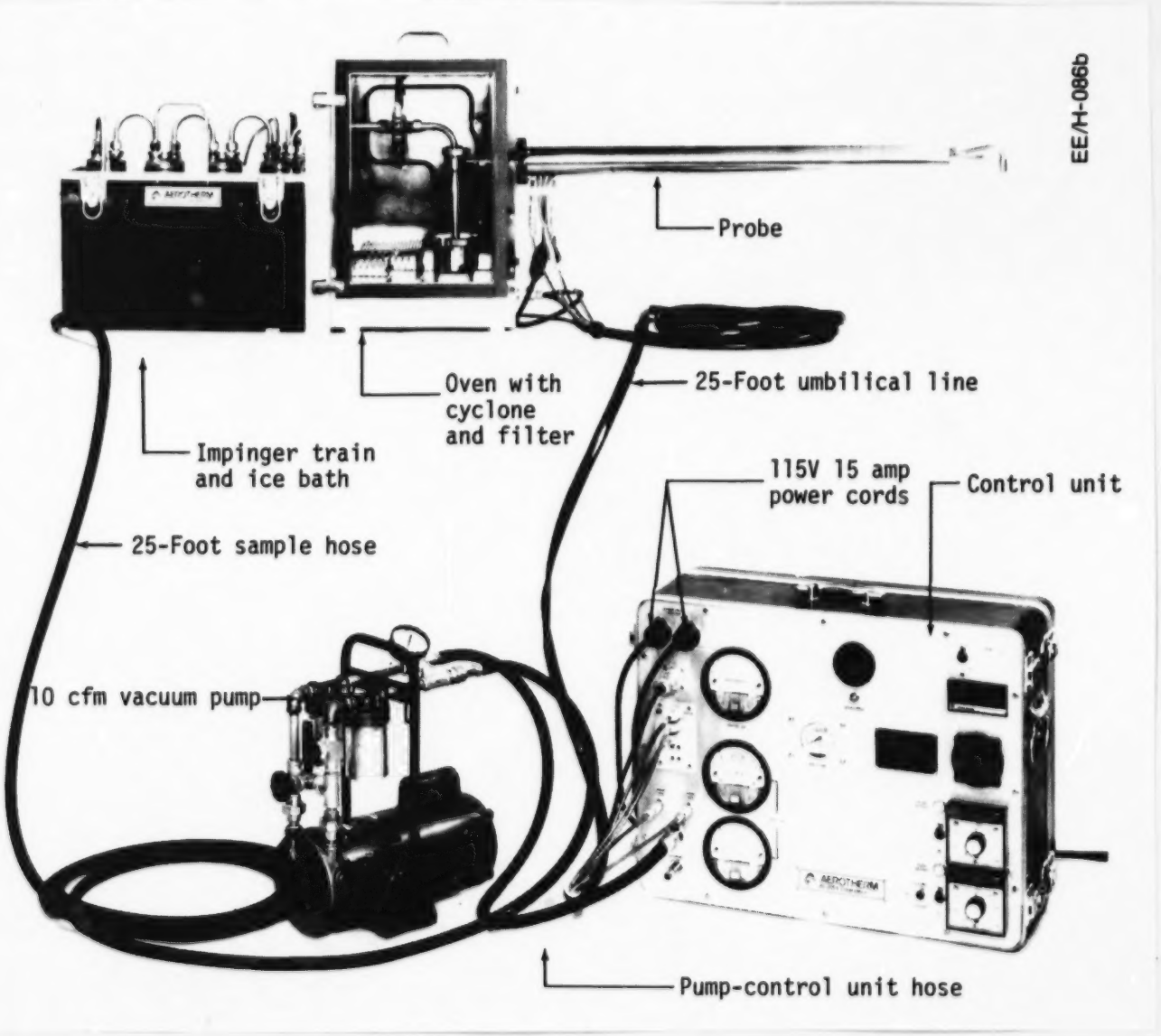


Figure A-2. Acurex high volume stack sampler.

Location from the duct wall, m (in.)

Point		
1	0.025	(1.0)
2	0.025	(1.0)
3	0.030	(1.18)
4	0.044	(1.71)
5	0.058	(2.30)
6	0.075	(2.96)
7	0.094	(3.72)
8	0.118	(4.66)
9	0.153	(6.02)

Figure A-3. Particulate sampling point locations for spark-ignited engine.

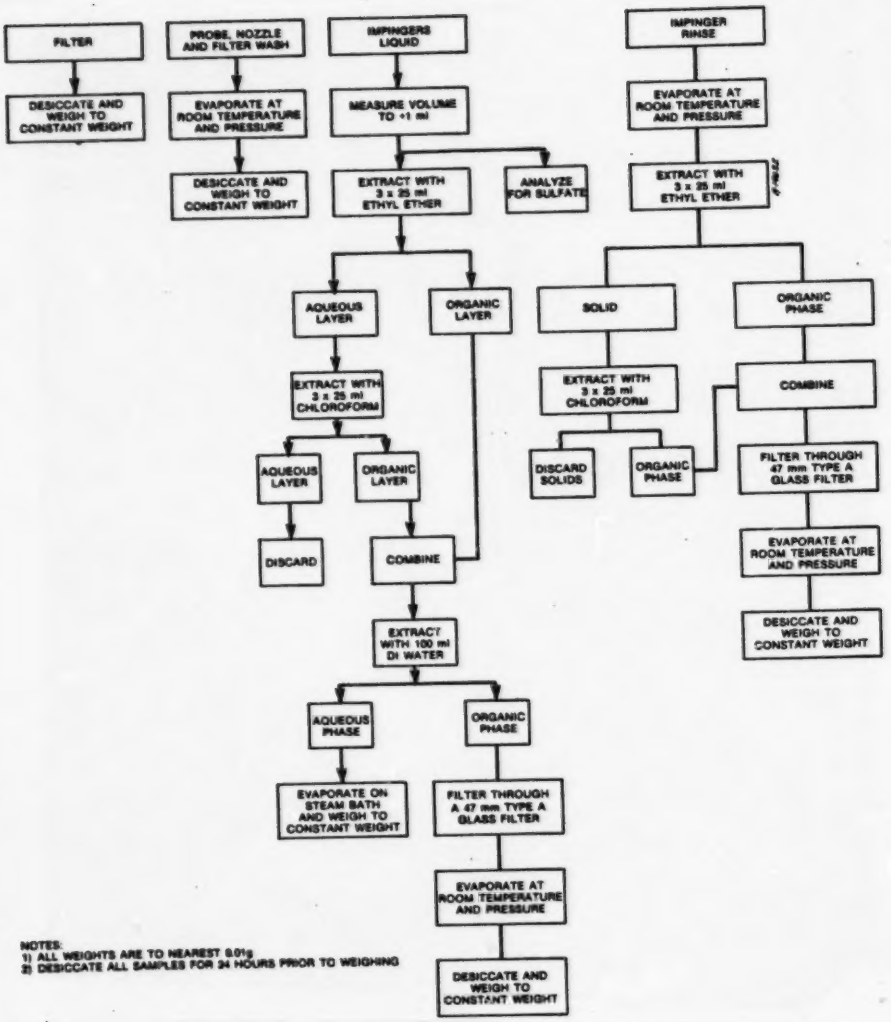

FILTER
PROBE, NOZZLE AND FILTER WASH
IMPINGERS LIQUID
IMPINGER RINSE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
MEASURE VOLUME TO +1 ml
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
EXTRACT WITH 3 x 25 ml ETHYL ETHER
ANALYZE FOR SULFATE
EXTRACT WITH 3 x 25 ml ETHYL ETHER
AQUEOUS LAYER
ORGANIC LAYER
SOLID
ORGANIC PHASE
EXTRACT WITH 3 x 25 ml CHLOROFORM
EXTRACT WITH 3 x 25 ml CHLOROFORM
COMBINE
AQUEOUS LAYER
ORGANIC LAYER
DISCARD SOLIDS
ORGANIC PHASE
FILTER THROUGH 47 mm TYPE A GLASS FILTER
DISCARD
COMBINE
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
EXTRACT WITH 100 ml DI WATER
AQUEOUS PHASE
ORGANIC PHASE
EVAPORATE ON STEAM BATH AND WEIGH TO CONSTANT WEIGHT
FILTER THROUGH A 47 mm TYPE A GLASS FILTER
EVAPORATE AT ROOM TEMPERATURE AND PRESSURE
DESICCATE AND WEIGH TO CONSTANT WEIGHT
NOTES:
1) ALL WEIGHTS ARE TO NEAREST 0.01g
2) DESICCATE ALL SAMPLES FOR 24 HOURS PRIOR TO WEIGHING

Figure A-4. Sample analysis scheme for particulate sampling train.

and impinger rinses. The impinger solutions are treated with ethyl ether to separate the organic matter from the liquid and solid samples.

A.3 TRACE ELEMENTS AND ORGANIC EMISSIONS

Emissions of inorganic trace elements and organic compounds were sampled with the SASS. Designed and built for EPA's Process Measurement Branch for Level 1 environmental assessment, the SASS collects large quantities of gas and solid samples required for subsequent analyses of inorganic and organic emissions as well as particle size measurement.

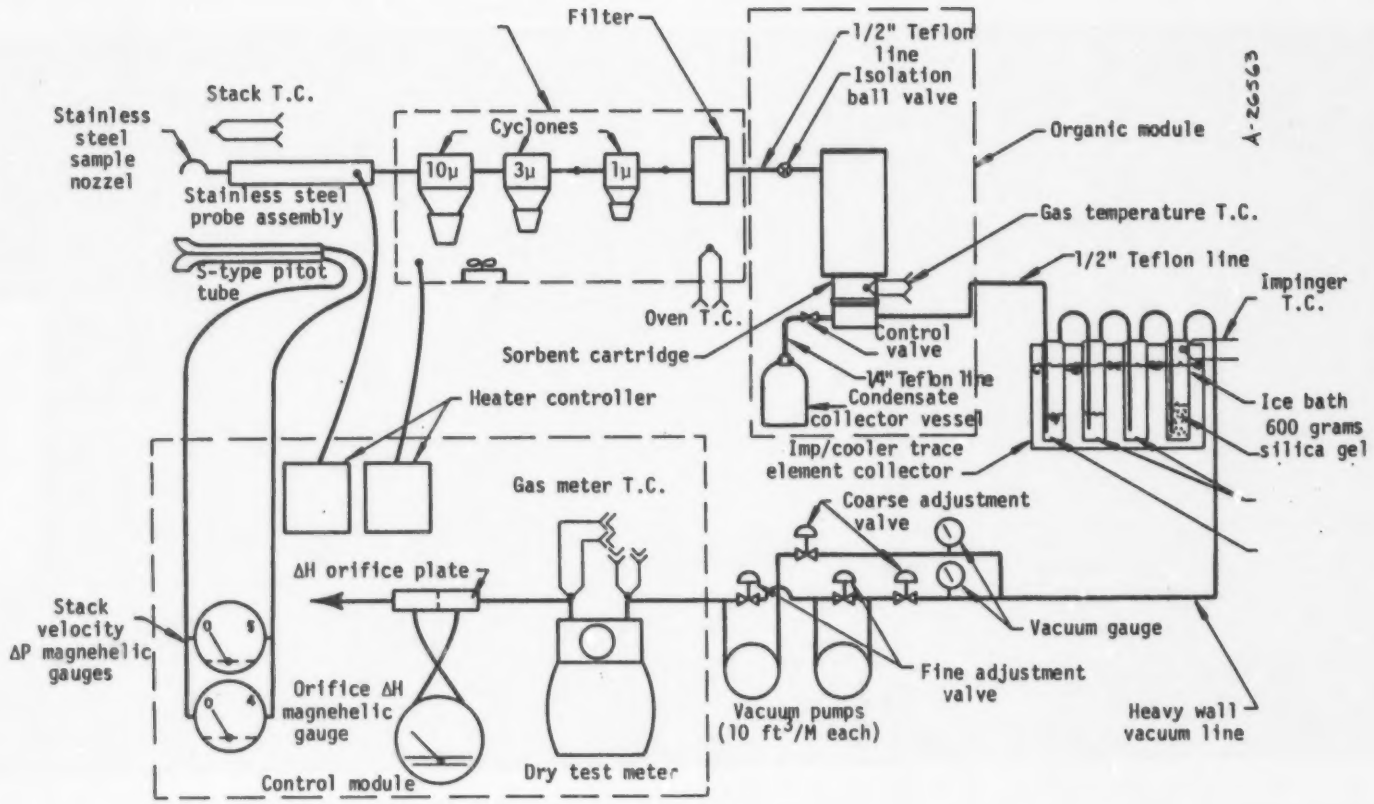
The SASS system, illustrated in figure A-5, is similar to the HVSS system utilized for total particulate mass emission tests described in the previous section with the exception of:

- Particulate cyclones heated in the oven with the filter to 500K (450°F)
- The addition of a gas cooler and organic sampling module
- The addition of necessary vacuum pumps

The cyclones were not used in this test program.

Schematics outlining the sampling and analytical procedures using the SASS equipment are presented in figures A-6 and A-7.

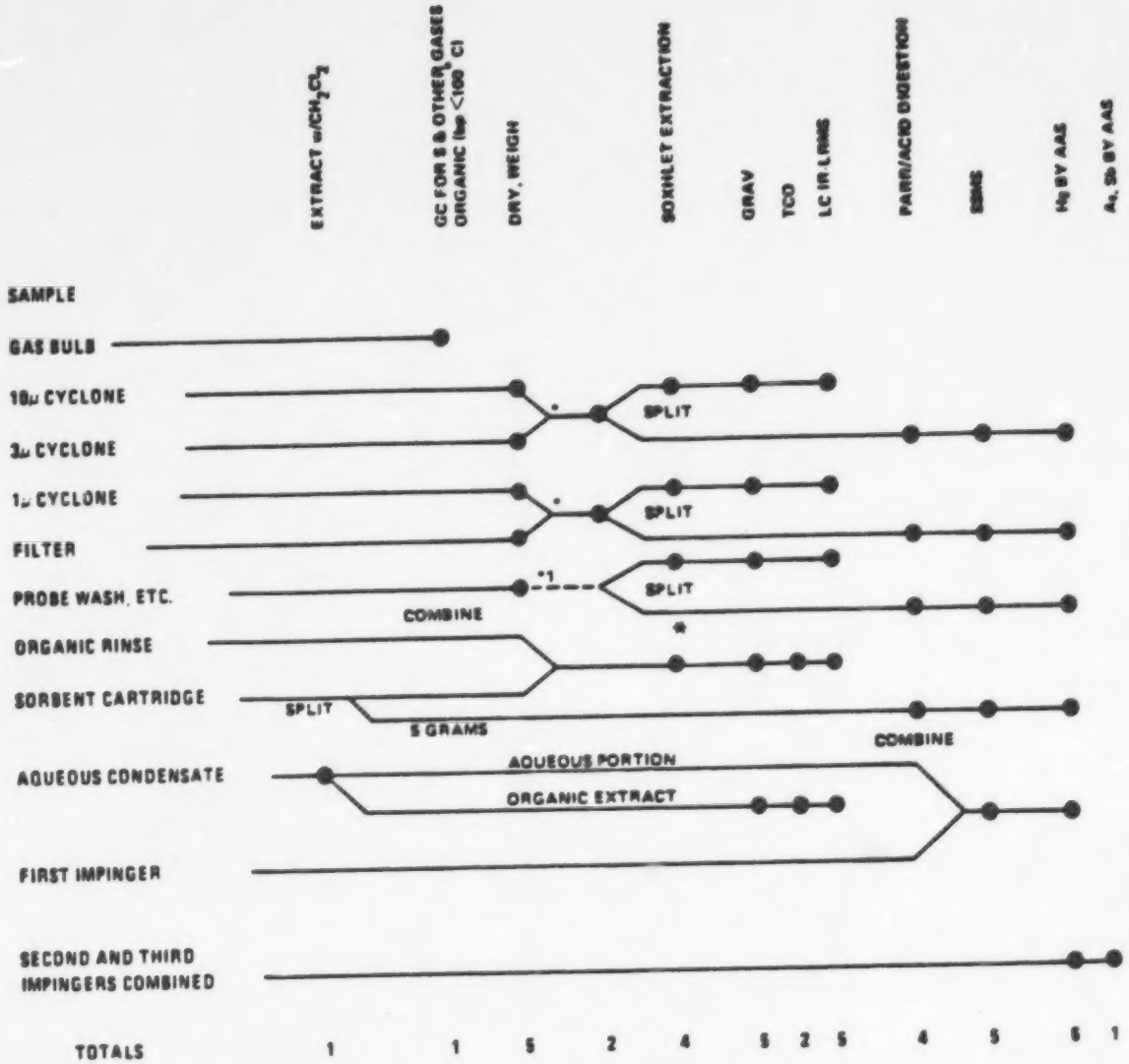
Inorganic analyses of solid and liquid samples from the SASS train were performed with SSMS for most of the trace elements. AAS was used for analyses of mercury (Hg), antimony (Sb), arsenic (As). Quantitative information on total organic emissions was obtained by TCO analyses and by gravimetry (GRAV) of methylene chloride extracts of samples collected on the filter and in the sorbent module (XAD-2) and condensate trap. GC/MS was used for POM and selected other organic species (the semivolatile organic priority pollutants) analyses of solid and liquid extract SASS samples. Figure A-8



A-12

A-2

Figure A-5. Source assessment sampling system schematic.



• If required, sample should be set aside for biological analysis at this point.

[1] This step is required to define the total mass of particulate catch. If the sample exceeds 10% of the total cyclone and filter sample weight proceed to analysis. If the sample is less than 10% of the catch, hold in reserve.

Figure A-6. Analysis protocol for SASS samples.

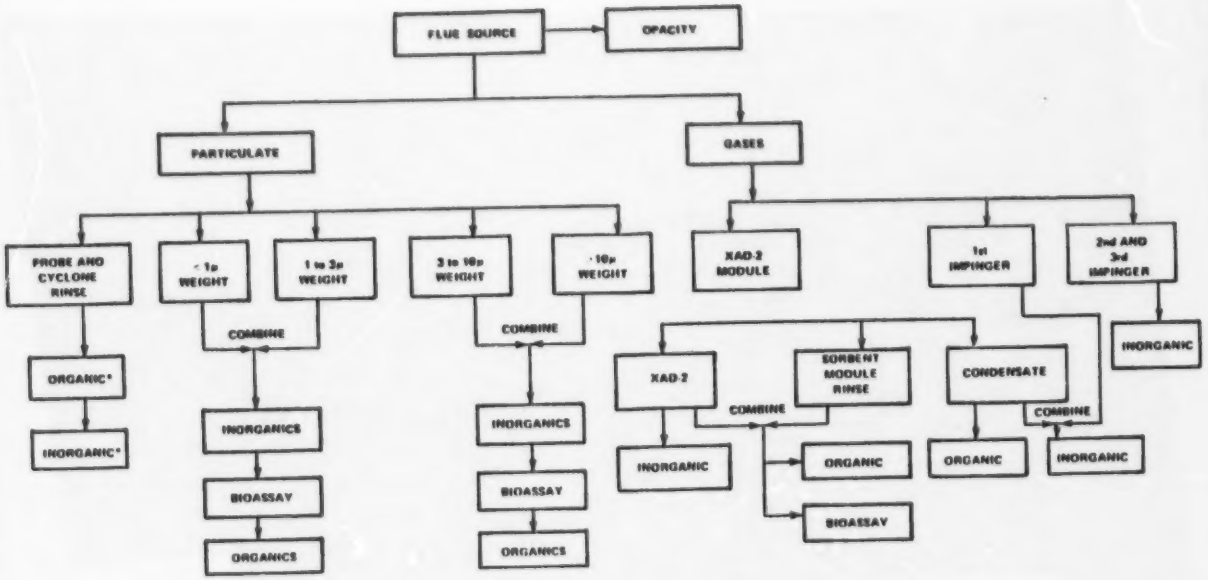
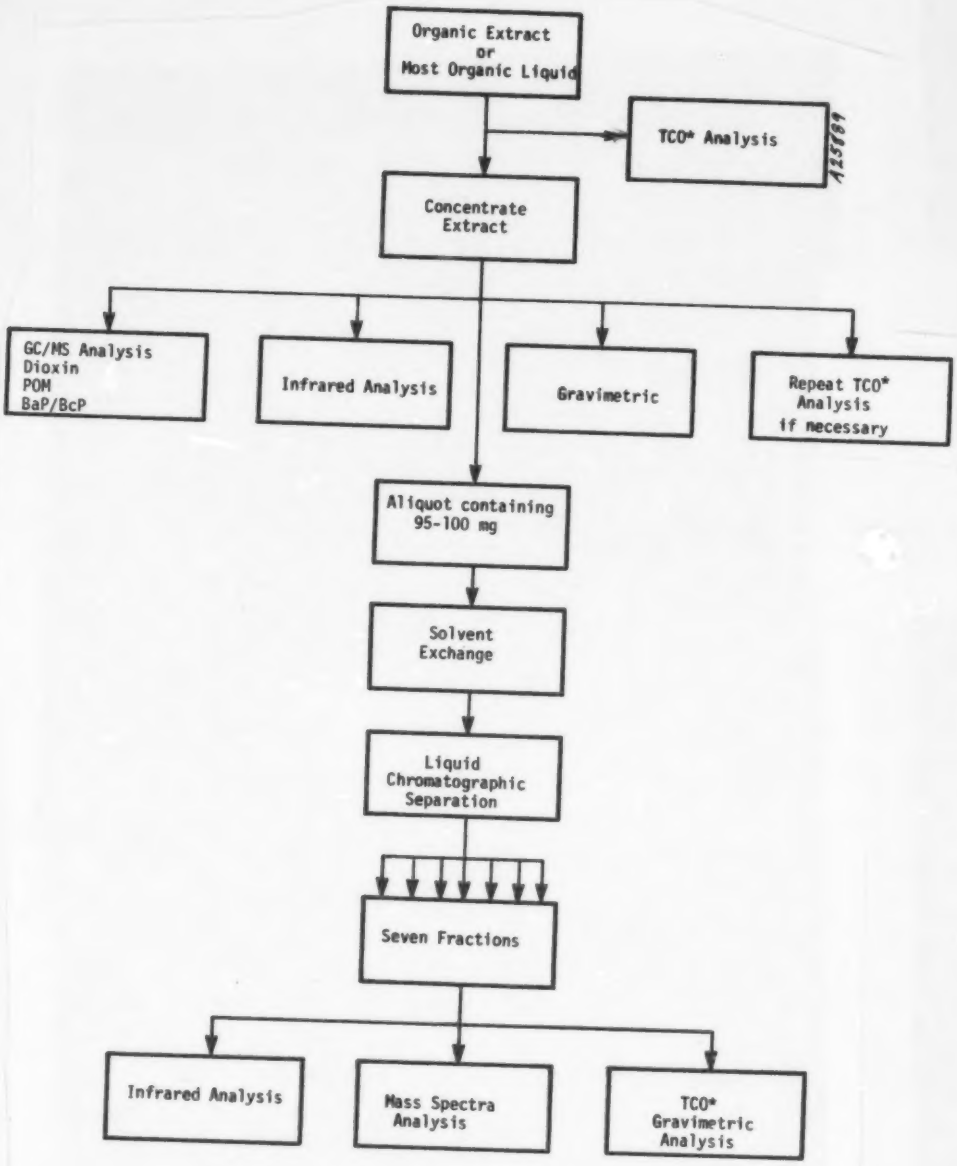


Figure A-7. Exhaust gas analysis protocol.



*TCO analyses are not necessary for sample for which process or collection temperatures were 200°C (400°F) or higher.

Figure A-8. Organic analysis methodology.

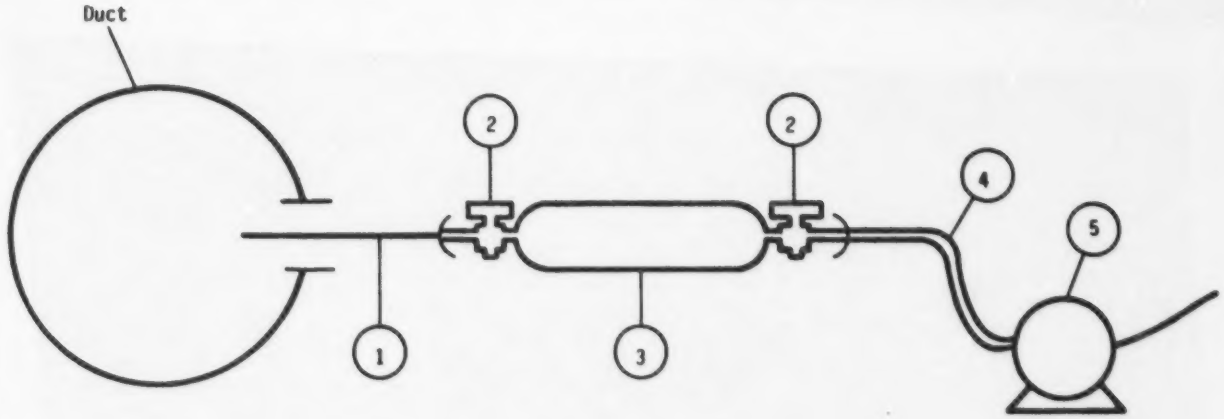
illustrates the organic analysis methodology followed during the current program.

Passivation of the SASS train with 15 percent by volume HNO_3 solution was performed prior to equipment preparation and sampling to produce biologically inert surfaces. Detailed description of equipment preparation, sampling procedures, and sample recovery are discussed in reference A-2 and will not be repeated here. These procedures were followed in the course of the current test program.

A.4 C_1 to C_6 HYDROCARBON SAMPLING AND ANALYSIS

Acurex used a grab sampling procedure in order to obtain a sample of exhaust gas for C_1 to C_6 hydrocarbon analysis. Samples of the exhaust gas were extracted using a heated glass probe (Figure A-9). The probe was attached to a heated 250-ml gas sampling bulb. The probe was maintained at 423K (300°F) and the gas sampling bulb at 403K (265°F). A diaphram pump was used to pull samples through the probe and sampling bulb. This purge was continued until all visual signs of condensation had disappeared. At that time, the back stopcock of the sampling bulb was closed and the pump was disconnected. Once the sampling bulb pressure had come to equilibrium with the stack pressure, the sample was sealed and transported to the laboratory for analysis.

The gas sampling bulbs were equipped with a septum port. A gas-tight syringe was used to extract a measured amount of sample. Samples were analyzed on a Gas Chromatograph (GC) with a Flame Ionization Detector (FID). Both methane and nonmethane hydrocarbons were measured with each injection. Onsite measurements were attempted using a Carle Model 8500 Gas Chromatograph with FID. However, because of instrument malfunction onsite, actual



1. Heated glass probe
2. Teflon stopcock
3. 250-ml heated glass gas sampling bulb
4. Tubing connection
5. Sample pump

Figure A-9. C_1 to C_6 hydrocargon sampling system.

determinations were performed on a Varian Model 3700 GC with FID, automatic injection loop, and an automatic linear temperature programming capability, located at the Acurex laboratory in Mountain View, California. Table A-2 details the instruments specifications.

The GC was calibrated before and after each test in order to determine instrument drift. Blank samples were also run in order to quantify any sampling equipment interferences.

Sample data were recorded continuously on a strip chart recorder. After the detection of the methane peak, the column was back-flushed to the detector for analysis of the remaining nonmethane hydrocarbons. Each gas sampling bulb was analyzed several times to ensure a representative sample analysis.

TABLE A-2. GAS CHROMATOGRAPH SPECIFICATIONS

Carle Instruments, Inc., Model 8500 gas chromatograph:	
Sensitivity:	5×10^{-12} amperes for 1 mV output
Suppression range:	10^{-9} amperes
Noise:	0.5% peak to peak on most sensitive range
Time constant:	100 milliseconds on all ranges except "1" range which is 200 milliseconds
Gas required:	Carrier gas (helium) Combustion air Fuel gas (hydrogen)
Varian Model 3700 gas chromatograph:	
Sensitivity:	1×10^{-12} A/mV at attenuation 1 and range 10^{-12} A/mV
Zero range:	-10^{-11} to 10^{-9}A (reversible with internal switch)
Noise (inputs capped):	5×10^{-15}A; 0.5 μV peak to peak
Time constant:	220 ms on all ranges (approximate 1 second response to 99% of peak)
Gas required:	Carrier gas (helium) Combustion air Fuel gas (hydrogen)

REFERENCES FOR APPENDIX A

A-1. "DEMA Exhaust Emission Measurement Procedure for Low and Medium Speed Internal Combustion Engines," Diesel Engine Manufacturers Association, Cleveland, Ohio, 1974.

A-2. Lentzen, D.E., et al., "IERL-RTP Procedures Manual; Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB293795, October 1978.

APPENDIX B

TRACE ELEMENT CONCENTRATIONS

The following tables present sample trace element analysis results and trace element discharge stream concentrations. The tables labeled "ppm" represent element analysis results (microgram per gram μg/g) for each sample analyzed. Composition for the engine lube oil and all SASS train samples (filter, XAD-2 resin, first impinger, and second and third impingers) are noted.

The tables labeled "mass/heat input" give calculated trace element concentrations in units of nanograms per Joules (ng/J) heat input for the lube oil and all SASS train samples. The column labeled "flue gas" represents the appropriate sum of SASS train samples.

The tables labeled "concentration" give the calculated flue gas concentration (μg/dscm) of each element corresponding to each SASS train sample, and the SASS train sum (labeled "flue gas").

The tables labeled "mass flow" give calculated element flowrates (μg/s) corresponding to each analyzed sample. These are summed in the tables labeled "engine mass-balance."

Symbols appearing in the tables:

DSCM	Dry standard cubic meter at 1 atm and 15°C
MCG	Microgram
PPM	Part per million by weight

SEC Second

< Less than

> Greater than

Trace elements having concentration less than the detectable limit or having a blank value greater than the sample value were given an arbitrary concentration of zero.

Detectability limits for the various SASS samples were the following:

- Filter -- <0.001 μg/cm^2
  - -- Baseline -- <2.1 μg/g
  - -- Low-NO_x -- <3.7 μg/g
- XAD-2 -- <0.1 μg/g
- Impinger and organic module concentrate -- <0.001 μ/ml
- Lube oil -- <0.03 μg/g

COLT-SPARK
BASELINE

PPM

ELEMENT	PPM LUBE-OIL	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3
ALUMINUM	>.370E+02	U.000E+00	.000E+00	U.000E+00	N.000E+00
ANTIMONY	.000E+00	.000E+00	.000E+00	.100E-02	<.600E-02
ARSENIC	<.200E+00	.000E+00	.000E+00	<.100E-02	<.200E-01
BARIUM	.100E+01	.000E+00	.100E+01	.200E-01	N.000E+00
BERYLLIUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
BISMUTH	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
BORON	.400E+00	.000E+00	.000E+00	.000E+00	N.000E+00
BROMINE	.300E+00	.000E+00	.100E+00	.170E-01	N.000E+00
CADMIUM	<.700E-01	<.308E+01	.000E+00	.000E+00	N.000E+00
CALCIUM	>.100E+03	U.000E+00	.000E+00	.700E+01	N.000E+00
CERIUM	.000E+00	.000E+00	.000E+00	.200E-02	N.000E+00
CESIUM	.000E+00	.000E+00	.000E+00	.200E-02	N.000E+00
CHLORINE	.130E+02	.000E+00	.000E+00	.100E+00	N.000E+00
CHROMIUM	.900E+01	.000E+00	.100E+01	.199E+00	N.000E+00
COBALT	.600E+00	.000E+00	.000E+00	.000E+00	N.000E+00
COPPER	.300E+01	.000E+00	.000E+00	.300E+01	N.000E+00
FLUORINE	.300E+01	.169E+03	.000E+00	.200E+00	N.000E+00
GALLIUM	.000E+00	.000E+00	.000E+00	.900E-02	N.000E+00
GERMANIUM	.000E+00	.615E+01	.000E+00	.100E-02	N.000E+00
GOLD	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
IODINE	.200E+00	.000E+00	.000E+00	.300E-02	N.000E+00
IRON	.300E+02	.000E+00	.000E+00	.000E+00	N.000E+00
LANTHANUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
LEAD	.100E+01	.000E+00	.000E+00	.230E+00	N.000E+00
LITHIUM	.200E+00	.308E+01	.000E+00	.000E+00	N.000E+00
MAGNESIUM	>.100E+03	.000E+00	.200E+01	.000E+00	N.000E+00
MANGANESE	.600E+00	.000E+00	.000E+00	.100E-01	N.000E+00
MERCURY	<.100E+00	.000E+00	<.100E+00	<.900E-03	<.200E-02
MOLYBDENUM	.800E+00	.292E+03	.560E+01	.100E-01	N.000E+00
NEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
NICKEL	.100E+01	.000E+00	U.000E+00	.270E+00	N.000E+00
NIOBIUM	.000E+00	.000E+00	.000E+00	.800E-02	N.000E+00
PHOSPHORUS	>.100E+03	.707E+03	.200E+01	.000E+00	N.000E+00
POTASSIUM	.460E+02	.000E+00	.000E+00	>.950E+01	N.000E+00
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
RUBIDIUM	.700E-01	.000E+00	.000E+00	.600E-02	N.000E+00
SCANDIUM	<.400E-01	.000E+00	.000E+00	<.100E-02	N.000E+00
SELENIUM	.000E+00	.000E+00	.000E+00	.700E+00	N.000E+00
SILICON	.430E+02	U.000E+00	U.000E+00	.400E+01	N.000E+00
SILVER	.000E+00	.000E+00	.000E+00	.200E-01	N.000E+00
SODIUM	>.960E+02	U.000E+00	.000E+00	>.950E+01	N.000E+00
STRONTIUM	.200E+01	.000E+00	.800E+00	.400E-02	N.000E+00
SULFUR	>.100E+03	>.283E+05	.110E+02	>.980E+01	N.000E+00
TANTALUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
TELLURIUM	.000E+00	.000E+00	.000E+00	.200E-01	N.000E+00

COLT-SPARK
BASELINE

PPM

ELEMENT	PPM LUBE-OIL	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
TIN	.900E+00	.615E+01	.000E+00	.100E-01	N.000E+00
TITANIUM	.900E+01	.000E+00	.000E+00	.000E+00	N.000E+00
TUNGSTEN	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
VANADIUM	.600E-01	.000E+00	.000E+00	.300E-02	N.000E+00
YTTRIUM	.000E+00	.000E+00	.000E+00	<.100E-02	N.000E+00
ZINC	>.100E+03	.584E+03	.000E+00	.197E+01	N.000E+00
ZIRCONIUM	.000E+00	.000E+00	.000E+00	<.100E-02	N.000E+00

COLT-SPARK
BASELINE

MASS/HEAT INPUT

NG/J

ELEMENT	LUBE-OIL	FLUE GAS
ALUMINUM	> .831E+00	.000E+00
ANTIMONY	.000E+00	.506E-04<X<.128E-03
ARSENIC	< .449E-02	< .308E-03
BARIUM	.225E-01	.389E-02
BERYLLIUM	.000E+00	.000E+00
BISMUTH	.000E+00	.000E+00
BORON	.899E-02	.000E+00
BROMINE	.674E-02	.115E-02
CADMIUM	< .157E-02	< .380E-05
CALCIUM	> .225E+01	.354E+00
CERIUM	.000E+00	.101E-03
CESIUM	.000E+00	.101E-03
CHLORINE	.292E+00	.506E-02
CHROMIUM	.202E+00	.129E-01
COBALT	.135E-01	.000E+00
COPPER	.674E-01	.152E+00
FLUORINE	.674E-01	.103E-01
GALLIUM	.000E+00	.455E-03
GERMANIUM	.000E+00	.582E-04
GOLD	.000E+00	.000E+00
IODINE	.449E-02	.152E-03
IRON	.674E+00	.000E+00
LANTHANUM	.000E+00	.000E+00
LEAD	.225E-01	.116E-01
LITHIUM	.449E-02	.380E-05
MAGNESIUM	> .225E+01	.576E-02
MANGANESE	.135E-01	.506E-03
MERCURY	< .225E-02	< .359E-03
MOLYBDENUM	.180E-01	.170E-01
NEODYMIUM	.000E+00	.000E+00
NICKEL	.225E-01	.137E-01
NIOBIUM	.000E+00	.404E-03
PHOSPHORUS	> .225E+01	.663E-02
POTASSIUM	.103E+01	> .480E+00
PRASEODYMIUM	.000E+00	.000E+00
RUBIDIUM	.157E-02	.303E-03
SCANDIUM	< .899E-03	< .506E-04
SELENIUM	.000E+00	.354E-01
SILICON	.966E+00	.202E+00
SILVER	.000E+00	.101E-02
SODIUM	> .216E+01	> .480E+00
STRONTIUM	.449E-01	.250E-02
SULFUR	> .225E+01	> .562E+00
TANTALUM	.000E+00	.000E+00
TELLURIUM	.000E+00	.101E-02

COLT-SPARK
BASELINE

MASS/HEAT INPUT

NG/J

ELEMENT	LUBE-OIL	FLUE GAS
THORIUM	.000E+00	.000E+00
TIN	.202E-01	.513E-03
TITANIUM	.202E+00	.000E+00
TUNGSTEN	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00
VANADIUM	.135E-02	.152E-03
YTTRIUM	.000E+00	< .506E-04
ZINC	> .225E+01	.100E+00
ZIRCONIUM	.000E+00	< .506E-04

COLT-SPARK
BASELINE

MASS/HEAT INPUT NG/J

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
ALUMINUM	U .000E+00	.000E+00	U .000E+00	N .000E+00	.000E+00
ANTIMONY	.000E+00	.000E+00	.506E-04	< .773E-04	.506E-04<X<.128E-03
ARSENIC	.000E+00	.000E+00	< .506E-04	< .258E-03	< .308E-03
BARIUM	.000E+00	.288E-02	.101E-02	N .000E+00	.389E-02
BERYLLIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BISMUTH	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BORON	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BROMINE	.000E+00	.288E-03	.859E-03	N .000E+00	.115E-02
CADMIUM	< .380E-05	.000E+00	.000E+00	N .000E+00	< .380E-05
CALCIUM	U .000E+00	.000E+00	.354E+00	N .000E+00	.354E+00
CERIUM	.000E+00	.000E+00	.101E-03	N .000E+00	.101E-03
CESIUM	.000E+00	.000E+00	.101E-03	N .000E+00	.101E-03
CHLORINE	.000E+00	.000E+00	.506E-02	N .000E+00	.506E-02
CHROMIUM	.000E+00	.288E-02	.101E-01	N .000E+00	.129E-01
COBALT	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
COPPER	.000E+00	.000E+00	.152E+00	N .000E+00	.152E+00
FLUORINE	.209E-03	.000E+00	.101E-01	N .000E+00	.103E-01
GALLIUM	.000E+00	.000E+00	.455E-03	N .000E+00	.455E-03
GERMANIUM	.760E-05	.000E+00	.506E-04	N .000E+00	.582E-04
GOLD	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
IODINE	.000E+00	.000E+00	.152E-03	N .000E+00	.152E-03
IRON	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
LANTHANUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
LEAD	.000E+00	.000E+00	.116E-01	N .000E+00	.116E-01
LITHIUM	.380E-05	.000E+00	.000E+00	N .000E+00	.380E-05
MAGNESIUM	.000E+00	.576E-02	.000E+00	N .000E+00	.576E-02
MANGANESE	.000E+00	.000E+00	.506E-03	N .000E+00	.506E-03
MERCURY	.000E+00	< .288E-03	< .455E-04	< .258E-04	< .359E-03
MOLYBDENUM	.361E-03	.161E-01	.506E-03	N .000E+00	.170E-01
NEODYMIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
NICKEL	.000E+00	U .000E+00	.137E-01	N .000E+00	.137E-01
NIOBIUM	.000E+00	.000E+00	.404E-03	N .000E+00	.404E-03
PHOSPHORUS	.874E-03	.576E-02	.000E+00	N .000E+00	.663E-02
POTASSIUM	.000E+00	.000E+00	> .480E+00	N .000E+00	> .480E+00
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	.303E-03	N .000E+00	.303E-03
SCANDIUM	.000E+00	.000E+00	< .506E-04	N .000E+00	< .506E-04
SELENIUM	.000E+00	.000E+00	.354E-01	N .000E+00	.354E-01
SILICON	U .000E+00	U .000E+00	.202E+00	N .000E+00	.202E+00
SILVER	.000E+00	.000E+00	.101E-02	N .000E+00	.101E-02
SODIUM	U .000E+00	.000E+00	> .480E+00	N .000E+00	> .480E+00
STRONTIUM	.000E+00	.230E-02	.202E-03	N .000E+00	.250E-02
SULFUR	> .349E-01	.317E-01	> .495E+00	N .000E+00	> .562E+00
TANTALUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TELLURIUM	.000E+00	.000E+00	.101E-02	N .000E+00	.101E-02

COLT-SPARK
BASELINE

MASS/HEAT INPUT
NG/J

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
THORIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TIN	.760E-05	.000E+00	.506E-03	N .000E+00	.513E-03
TITANIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TUNGSTEN	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
VANADIUM	.000E+00	.000E+00	.152E-03	N .000E+00	.152E-03
YTTRIUM	.000E+00	.000E+00	< .506E-04	N .000E+00	< .506E-04
ZINC	.722E-03	.000E+00	.996E-01	N .000E+00	.100E+00
ZIRCONIUM	.000E+00	.000E+00	< .506E-04	N .000E+00	< .506E-04

COLT-SPARK
BASELINE
MCG/DSCM

CONCENTRATION ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
ALUMINUM	U .000E+00	.000E+00	U .000E+00	N .000E+00	.000E+00
ANTIMONY	.000E+00	.000E+00	.847E-01	< .129E+00	.847E-01<X<.214E+00
ARSENIC	.000E+00	.000E+00	< .847E-01	< .431E+00	< .516E+00
BARIUM	.000E+00	.482E+01	.169E+01	N .000E+00	.651E+01
BERYLLIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BISMUTH	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BORON	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BROMINE	.000E+00	.482E+00	.144E+01	N .000E+00	.192E+01
CADMIUM	< .636E-02	.000E+00	.000E+00	N .000E+00	< .636E-02
CALCIUM	U .000E+00	.000E+00	.593E+03	N .000E+00	.593E+03
CERIUM	.000E+00	.000E+00	.169E+00	N .000E+00	.169E+00
CESIUM	.000E+00	.000E+00	.169E+00	N .000E+00	.169E+00
CHLORINE	.000E+00	.000E+00	.847E+01	N .000E+00	.847E+01
CHROMIUM	.000E+00	.482E+01	.168E+02	N .000E+00	.217E+02
COBALT	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
COPPER	.000E+00	.000E+00	.254E+03	N .000E+00	.254E+03
FLUORINE	.350E+00	.000E+00	.169E+02	N .000E+00	.173E+02
GALLIUM	.000E+00	.000E+00	.762E+00	N .000E+00	.762E+00
GERMANIUM	.127E-01	.000E+00	.847E-01	N .000E+00	.974E-01
GOLD	.000E+00	.000E+00	.000E+00	N .000E+00	000E+00
IODINE	.000E+00	.000E+00	.254E+00	N .000E+00	.254E+00
IRON	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
LANTHANUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
LEAD	.000E+00	.000E+00	.195E+02	N .000E+00	.195E+02
LITHIUM	.636E-02	.000E+00	.000E+00	N .000E+00	.636E-02
MAGNESIUM	.000E+00	.964E+01	.000E+00	N .000E+00	.964E+01
MANGANESE	.000E+00	.000E+00	.847E+00	N .000E+00	.847E+00
MERCURY	.000E+00	< .482E+00	< .762E-01	< .431E-01	< .601E+00
MOLYBDENUM	.604E+00	.270E+02	.847E+00	N .000E+00	.284E+02
NEODYMIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
NICKEL	.000E+00	U .000E+00	.229E+02	N .000E+00	.229E+02
NIOBIUM	.000E+00	.000E+00	.677E+00	N .000E+00	.677E+00
PHOSPHORUS	.146E+01	.964E+01	.000E+00	N .000E+00	.111E+02
POTASSIUM	.000E+00	.000E+00	> .804E+03	N .000E+00	> .804E+03
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	.508E+00	N .000E+00	.508E+00
SCANDIUM	.000E+00	.000E+00	< .847E-01	N .000E+00	< .847E-01
SELENIUM	.000E+00	.000E+00	.593E+02	N .000E+00	.593E+02
SILICON	U .000E+00	U .000E+00	.339E+03	N .000E+00	.339E+03
SILVER	.000E+00	.000E+00	.169E+01	N .000E+00	.169E+01
SODIUM	U .000E+00	.000E+00	> .804E+03	N .000E+00	> .804E+03
STRONTIUM	.000E+00	.386E+01	.339E+00	N .000E+00	.419E+01
SULFUR	> .585E+02	.530E+02	> .830E+03	N .000E+00	> .941E+03
TANTALUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TELLURIUM	.000E+00	.000E+00	.169E+01	N .000E+00	.169E+01

CONCENTRATION — COLT-SPARK BASELINE — MCG/DSCM

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
THORIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TIN	.127E-01	.000E+00	.847E+00	N .000E+00	.859E+00
TITANIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TUNGSTEN	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
VANADIUM	.000E+00	.000E+00	.254E+00	N .000E+00	.254E+00
YTTRIUM	.000E+00	.000E+00	< .847E-01	N .000E+00	< .847E-01
ZINC	.121E+01	.000E+00	.167E+03	N .000E+00	.168E+03
ZIRCONIUM	.000E+00	.000E+00	< .847E-01	N .000E+00	< .847E-01

COLT-SPARK
BASELINE

MASS FLOW
MCG/SEC

ELEMENT	LUBE-OIL	FLUE GAS
ALUMINUM	> .149E+02	.000E+00
ANTIMONY	.000E+00	.182E+00<X<.460E+00
ARSENIC	< .804E-01	< .111E+01
BARIUM	.402E+00	.140E+02
BERYLLIUM	.000E+00	.000E+00
BISMUTH	.000E+00	.000E+00
BORON	.161E+00	.000E+00
BROMINE	.121E+00	.413E+01
CADMIUM	< .281E-01	< .137E-01
CALCIUM	> .402E+02	.127E+04
CERIUM	.000E+00	.364E+00
CESIUM	.000E+00	.364E+00
CHLORINE	.523E+01	.182E+02
CHROMIUM	.362E+01	.466E+02
COBALT	.241E+00	.000E+00
COPPER	.121E+01	.546E+03
FLUORINE	.121E+01	.372E+02
GALLIUM	.000E+00	.164E+01
GERMANIUM	.000E+00	.209E+00
GOLD	.000E+00	.000E+00
IODINE	.804E-01	.546E+00
IRON	.121E+02	.000E+00
LANTHANUM	.000E+00	.000E+00
LEAD	.402E+00	.419E+02
LITHIUM	.804E-01	.137E-01
MAGNESIUM	> .402E+02	.207E+02
MANGANESE	.241E+00	.182E+01
MERCURY	< .402E-01	< .129E+01
MOLYBDENUM	.322E+00	.612E+02
NEODYMIUM	.000E+00	.000E+00
NICKEL	.402E+00	.492E+02
NIOBIUM	.000E+00	.146E+01
PHOSPHORUS	> .402E+02	.239E+02
POTASSIUM	.185E+02	> .173E+04
PRASEODYMIUM	.000E+00	.000E+00
RUBIDIUM	.281E-01	.109E+01
SCANDIUM	< .161E-01	< .182E+00
SELENIUM	.000E+00	.127E+03
SILICON	.173E+02	.728E+03
SILVER	.000E+00	.364E+01
SODIUM	> .386E+02	> .173E+04
STRONTIUM	.804E+00	.902E+01
SULFUR	> .402E+02	> .202E+04
TANTALUM	.000E+00	.000E+00
TELLURIUM	.000E+00	.364E+01

COLT-SPARK
BASELINE

MASS FLOW
MCG/SEC

ELEMENT	LUBE-OIL	FLUE GAS
THORIUM	.000E+00	.000E+00
TIN	.362E+00	.185E+01
TITANIUM	.362E+01	.000E+00
TUNGSTEN	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00
VANADIUM	.241E-01	.546E+00
YTTRIUM	.000E+00	< .182E+00
ZINC	> .402E+02	.361E+03
ZIRCONIUM	.000E+00	< .182E+00

COLT-SPARK
BASELINE

MASS FLOW
MCG/SEC

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
ALUMINUM	U .000E+00	.000E+00	U .000E+00	N .000E+00	.000E+00
ANTIMONY	.000E+00	.000E+00	.182E+00	< .278E+00	.182E+00<X<.460E+00
ARSENIC	.000E+00	.000E+00	< .182E+00	< .928E+00	< .111E+01
BARIUM	.000E+00	.104E+02	.364E+01	N .000E+00	.140E+02
BERYLLIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BISMUTH	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BORON	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BROMINE	.000E+00	.104E+01	.310E+01	N .000E+00	.413E+01
CADMIUM	< .137E-01	.000E+00	.000E+00	N .000E+00	< .137E-01
CALCIUM	U .000E+00	.000E+00	.127E+04	N .000E+00	.127E+04
CERIUM	.000E+00	.000E+00	.364E+00	N .000E+00	.364E+00
CESIUM	.000E+00	.000E+00	.364E+00	N .000E+00	.364E+00
CHLORINE	.000E+00	.000E+00	.182E+02	N .000E+00	.182E+02
CHROMIUM	.000E+00	.104E+02	.362E+02	N .000E+00	.466E+02
COBALT	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
COPPER	.000E+00	.000E+00	.546E+03	N .000E+00	.546E+03
FLUORINE	.752E+00	.000E+00	.364E+02	N .000E+00	.372E+02
GALLIUM	.000E+00	.000E+00	.164E+01	N .000E+00	.164E+01
GERMANIUM	.274E-01	.000E+00	.182E+00	N .000E+00	.209E+00
GOLD	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
IODINE	.000E+00	.000E+00	.546E+00	N .000E+00	.546E+00
IRON	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
LANTHANUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
LEAD	.000E+00	.000E+00	.419E+02	N .000E+00	.419E+02
LITHIUM	.137E-01	.000E+00	.000E+00	N .000E+00	.137E-01
MAGNESIUM	.000E+00	.207E+02	.000E+00	N .000E+00	.207E+02
MANGANESE	.000E+00	.000E+00	.182E+01	N .000E+00	.182E+01
MERCURY	.000E+00	< .104E+01	< .164E+00	< .928E-01	< .129E+01
MOLYBDENUM	.130E+01	.581E+02	.182E+01	N .000E+00	.612E+02
NEODYMIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
NICKEL	.000E+00	U .000E+00	.492E+02	N .000E+00	.492E+02
NIOBIUM	.000E+00	.000E+00	.146E+01	N .000E+00	.146E+01
PHOSPHORUS	.315E+01	.207E+02	.000E+00	N .000E+00	.239E+02
POTASSIUM	.000E+00	.000E+00	> .173E+04	N .000E+00	> .173E+04
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	.109E+01	N .000E+00	.109E+01
SCANDIUM	.000E+00	.000E+00	< .182E+00	N .000E+00	< .182E+00
SELENIUM	.000E+00	.000E+00	.127E+03	N .000E+00	.127E+03
SILICON	U .000E+00	U .000E+00	.728E+03	N .000E+00	.728E+03
SILVER	.000E+00	.000E+00	.364E+01	N .000E+00	.364E+01
SODIUM	U .000E+00	.000E+00	> .173E+04	N .000E+00	> .173E+04
STRONTIUM	.000E+00	.829E+01	.728E+00	N .000E+00	.902E+01
SULFUR	> .126E+03	.114E+03	> .178E+04	N .000E+00	> .202E+04
TANTALUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TELLURIUM	.000E+00	.000E+00	.364E+01	N .000E+00	.364E+01

COLT-SPARK
BASELINE

MASS FLOW
MCG/SEC

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
THORIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TIN	.274E-01	.000E+00	.182E+01	N .000E+00	.185E+01
TITANIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TUNGSTEN	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
VANADIUM	.000E+00	.000E+00	.546E+00	N .000E+00	.546E+00
YTTRIUM	.000E+00	.000E+00	< .182E+00	N .000E+00	< .182E+00
ZINC	.260E+01	.000E+00	.359E+03	N .000E+00	.361E+03
ZIRCONIUM	.000E+00	.000E+00	< .182E+00	N .000E+00	< .182E+00

COLT-SPARK
BASELINE

ENGINE MASS-BALANCE
INPUT=LUBE-OIL OUTPUT=EXHAUST

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
ALUMINUM	.149E+02 <X		.000E+00
ANTIMONY		.182E+00<X<.460E+00	*
ARSENIC	X<.804E-01	X<.111E+01	*
BARIUM	.402E+00	.140E+02	.348E+02
BERYLLIUM			*
BISMUTH			*
BORON	.161E+00		.000E+00
BROMINE	.121E+00	.413E+01	.343E+02
CADMIUM	X<.281E-01	X<.137E-01	*
CALCIUM	.402E+02 <X	.127E+04	X<.317E+02
CERIUM		.364E+00	*
CESIUM		.364E+00	*
CHLORINE	.523E+01	.182E+02	.348E+01
CHROMIUM	.362E+01	.466E+02	.129E+02
COBALT	.241E+00		.000E+00
COPPER	.121E+01	.546E+03	.453E+03
FLUORINE	.121E+01	.372E+02	.308E+02
GALLIUM		.164E+01	*
GERMANIUM		.209E+00	*
GOLD			*
IODINE	.804E-01	.546E+00	.679E+01
IRON	.121E+02		.000E+00
LANTHANUM			*
LEAD	.402E+00	.419E+02	.104E+03
LITHIUM	.804E-01	.137E-01	.170E+00
MAGNESIUM	.402E+02 <X	.207E+02	X<.516E+00
MANGANESE	.241E+00	.182E+01	.755E+01
MERCURY	X<.402E-01	X<.129E+01	*
MOLYBDENUM	.322E+00	.612E+02	.190E+03
NEODYMIUM			*
NICKEL	.402E+00	.492E+02	.122E+03
NIOBIUM		.146E+01	*
PHOSPHORUS	.402E+02 <X	.239E+02	X<.594E+00
POTASSIUM	.185E+02	.173E+04 <X	.935E+02 <X
PRASEODYMIUM			*
RUBIDIUM	.281E-01	.109E+01	.388E+02
SCANDIUM	X<.161E-01	X<.182E+00	*
SELENIUM		.127E+03	*
SILICON	.173E+02	.728E+03	.421E+02
SILVER		.364E+01	*
SODIUM	.386E+02 <X	.173E+04 <X	*
STRONTIUM	.804E+00	.902E+01	.112E+02
SULFUR	.402E+02 <X	.202E+04 <X	*
TANTALUM			*
TELLURIUM		.364E+01	*

COLT-SPARK
BASELINE

ENGINE MASS-BALANCE
INPUT=LUBE-OIL 0UTPUT=EXHAUST

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
THORIUM			*
TIN	.362E+00	.185E+01	.511E+01
TITANIUM	.362E+01		.000E+00
TUNGSTEN			*
URANIUM			*
VANADIUM	.241E-01	.546E+00	.226E+02
YTTRIUM		X<.182E+00	*
ZINC	.402E+02 <X	.361E+03	X<.899E+01
ZIRCONIUM		X<.182E+00	*

COLT-SPARK
LOW-NOX

PPM

ELEMENT	PPM LUBE-OIL	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3
ALUMINUM	>.370E+02	U.000E+00	.400E+01	U.000E+00	N.000E+00
ANTIMONY	.000E+00	<.601E+00	.000E+00	.000E+00	<.600E-02
ARSENIC	<.200E+00	.000E+00	.000E+00	<.100E-02	<.200E-01
BARIUM	.100E+01	.000E+00	.100E+01	.000E+00	N.000E+00
BERYLLIUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
BISMUTH	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
BORON	.400E+00	.601E+02	.800E+00	.000E+00	N.000E+00
BROMINE	.300E+00	.000E+00	.000E+00	.470E-01	N.000E+00
CADMIUM	<.700E-01	<.601E+00	.000E+00	.000E+00	N.000E+00
CALCIUM	>.100E+03	U.000E+00	.600E+02	.000E+00	N.000E+00
CERIUM	.000E+00	.000E+00	.100E+00	.000E+00	N.000E+00
CESIUM	.000E+00	<.601E+00	.000E+00	<.100E-02	N.000E+00
CHLORINE	.130E+02	.000E+00	.000E+00	.900E+00	N.000E+00
CHROMIUM	.900E+01	.360E+02	.170E+02	.190E-01	N.000E+00
COBALT	.600E+00	.000E+00	.600E+01	.000E+00	N.000E+00
COPPER	.300E+01	.180E+02	.410E+02	.999E+00	N.000E+00
FLUORINE	.300E+01	.237E+03	.000E+00	.200E+00	N.000E+00
GALLIUM	.000E+00	.000E+00	.200E+00	.200E-01	N.000E+00
GERMANIUM	.000E+00	<.601E+00	.000E+00	<.100E-02	N.000E+00
GOLD	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
IODINE	.200E+00	.000E+00	.000E+00	.100E-02	N.000E+00
IRON	.300E+02	.120E+03	.360E+03	.000E+00	N.000E+00
LANTHANUM	.000E+00	.000E+00	.000E+00	.400E-01	N.000E+00
LEAD	.100E+01	.781E+01	.000E+00	.130E+00	N.000E+00
LITHIUM	.200E+00	.114E+02	.000E+00	.200E-02	N.000E+00
MAGNESIUM	>.100E+03	.120E+04	.100E+01	.000E+00	N.000E+00
MANGANESE	.600E+00	.300E+01	.120E+02	.000E+00	N.000E+00
MERCURY	<.100E+00	.000E+00	<.100E+00	<.900E-03	<.200E-02
MOLYBDENUM	.800E+00	.120E+01	.600E+00	.000E+00	N.000E+00
NEODYMIUM	.000E+00	.000E+00	.100E+00	.000E+00	N.000E+00
NICKEL	.100E+01	.240E+02	U.000E+00	.200E-01	N.000E+00
NIOBIUM	.000E+00	.000E+00	.000E+00	.200E-02	N.000E+00
PHOSPHORUS	>.100E+03	.356E+04	.120E+02	.000E+00	N.000E+00
POTASSIUM	.460E+02	.000E+00	.210E+02	>.105E+02	N.000E+00
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
RUBIDIUM	.700E-01	.000E+00	.000E+00	.200E-02	N.000E+00
SAMARIUM	.000E+00	<.601E+00	.000E+00	.000E+00	.000E+00
SCANDIUM	<.400E-01	.000E+00	.000E+00	<.100E-02	N.000E+00
SELENIUM	.000E+00	.000E+00	.000E+00	.400E+00	N.000E+00
SILICON	.430E+02	U.000E+00	U.000E+00	.400E+01	N.000E+00
SILVER	.000E+00	.541E+01	.000E+00	.800E-01	N.000E+00
SODIUM	>.960E+02	U.000E+00	.000E+00	>.950E+01	N.000E+00
STRONTIUM	.200E+01	.601E+01	.100E+00	.100E-01	N.000E+00
SULFUR	>.100E+03	>.553E+04	.700E+01	>.980E+01	N.000E+00
TANTALUM	.000E+00	.000E+00	<.200E+00	.000E+00	N.000E+00

COLT-SPARK
LOW-NOX

PPM

ELEMENT	LUBE-OIL PPM	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3
TELLURIUM	.000E+00	.000E+00	.000E+00	.700E-02	N.000E+00
THORIUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
TIN	.900E+00	.300E+01	<.300E+00	.300E-02	N.000E+00
TITANIUM	.900E+01	.000E+00	.400E+01	.000E+00	N.000E+00
TUNGSTEN	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	.000E+00	N.000E+00
VANADIUM	.600E-01	.000E+00	.200E+00	.100E-02	N.000E+00
YTTRIUM	.000E+00	.000E+00	.000E+00	<.100E-02	N.000E+00
ZINC	>.100E+03	.415E+03	.500E+01	.197E+01	N.000E+00
ZIRCONIUM	.000E+00	.000E+00	.000E+00	.300E-02	N.000E+00

COLT-SPARK
LOW-NOX

MASS/HEAT INPUT

NG/J

ELEMENT	LUBE-OIL	FLUE GAS
ALUMINUM	> .831E+00	.122E-01
ANTIMONY	.000E+00	< .829E-04
ARSENIC	< .449E-02	< .319E-03
BARIUM	.225E-01	.304E-02
BERYLLIUM	.000E+00	.000E+00
BISMUTH	.000E+00	.000E+00
BORON	.899E-02	.284E-02
BROMINE	.674E-02	.266E-02
CADMIUM	< .157E-02	< .402E-05
CALCIUM	> .225E+01	.183E+00
CERIUM	.000E+00	.304E-03
CESIUM	.000E+00	< .606E-04
CHLORINE	.292E+00	.509E-01
CHROMIUM	.202E+00	.531E-01
COBALT	.135E-01	.183E-01
COPPER	674E-01	.181E+00
FLUORINE	.674E-01	.129E-01
GALLIUM	.000E+00	.174E-02
GERMANIUM	.000E+00	< .606E-04
GOLD	.000E+00	.000E+00
IODINE	.449E-02	.565E-04
IRON	.674E+00	.110E+01
LANTHANUM	.000E+00	.226E-02
LEAD	.225E-01	.740E-02
LITHIUM	.449E-02	.189E-03
MAGNESIUM	> .225E+01	.111E-01
MANGANESE	.135E-01	.365E-01
MERCURY	< .225E-02	< .382E-03
MOLYBDENUM	.180E-01	.183E-02
NEODYMIUM	.000E+00	.304E-03
NICKEL	.225E-01	.129E-02
NIOBIUM	.000E+00	.113E-03
PHOSPHORUS	> .225E+01	.603E-01
POTASSIUM	.103E+01	> .658E+00
PRASEODYMIUM	.000E+00	.000E+00
RUBIDIUM	.157E-02	.113E-03
SAMARIUM	.000E+00	< .402E-05
SCANDIUM	< .899E-03	< .565E-04
SELENIUM	.000E+00	.226E-01
SILICON	.966E+00	.226E+00
SILVER	.000E+00	.456E-02
SODIUM	> .216E+01	> .537E+00
STRONTIUM	.449E-01	.910E-03
SULFUR	> .225E+01	> .612E+00
TANTALUM	.000E+00	< .609E-03

COLT-SPARK
LOW-NOX

MASS/HEAT INPUT

NG/J

ELEMENT	LUBE-OIL	FLUE GAS
TELLURIUM	.000E+00	.396E-03
THORIUM	.000E+00	.000E+00
TIN	.202E-01	.190E-03<X<.110E-02
TITANIUM	.202E+00	.122E-01
TUNGSTEN	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00
VANADIUM	.135E-02	.665E-03
YTTRIUM	.000E+00	< .565E-04
ZINC	> .225E+01	.129E+00
ZIRCONIUM	.000E+00	.170E-03

COLT-SPARK
LOW-NOX

MASS/HEAT INPUT NG/J

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
ALUMINUM	U .000E+00	.122E-01	U .000E+00	N .000E+00	.122E-01
ANTIMONY	< .402E-05	.000E+00	.000E+00	< .788E-04	< .829E-04
ARSENIC	.000E+00	.000E+00	< .565E-04	< .263E-03	< .319E-03
BARIUM	.000E+00	.304E-02	.000E+00	N .000E+00	.304E-02
BERYLLIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BISMUTH	.000E+00	.000E+30	.000E+00	N .000E+00	.000E+00
BORON	.402E-03	.244E-02	.000E+00	N .000E+00	.284E-02
BROMINE	.000E+00	.000E+00	.266E-02	N .000E+00	.266E-02
CADMIUM	< .402E-05	.000E+00	.000E+00	N .000E+00	< .402E-05
CALCIUM	U .000E+00	.183E+00	.000E+00	N .000E+00	.183E+00
CERIUM	.000E+00	.304E-03	.000E+00	N .000E+00	.304E-03
CESIUM	< .402E-05	.000E+00	< .565E-04	N .000E+00	< .606E-04
CHLORINE	.000E+00	.000E+00	.509E-01	N .000E+00	.509E-01
CHROMIUM	.241E-03	.517E-01	.107E-02	N .000E+00	.531E-01
COBALT	.000E+00	.183E-01	.000E+00	N .000E+00	.183E-01
COPPER	.121E-03	.125E+00	.565E-01	N .000E+00	.181E+00
FLUORINE	.159E-02	.000E+00	.113E-01	N .000E+00	.129E-01
GALLIUM	.000E+00	.609E-03	.113E-02	N .000E+00	.174E-02
GERMANIUM	< .402E-05	.000E+00	< .565E-04	N .000E+00	< .606E-04
GOLD	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
IODINE	.000E+00	.000E+00	.565E-04	N .000E+00	.565E-04
IRON	.803E-03	.110E+01	.000E+00	N .000E+00	.110E+01
LANTHANUM	.000E+00	.000E+00	.226E-02	N .000E+00	.226E-02
LEAD	.522E-04	.000E+00	.735E-02	N .000E+00	.740E-02
LITHIUM	.763E-04	.000E+00	.113E-03	N .000E+00	.189E-03
MAGNESIUM	.803E-02	304E-02	.000E+00	N .000E+00	.111E-01
MANGANESE	.201E-04	.365E-01	.000E+00	N .000E+00	.365E-01
MERCURY	.000E+00	< .304E-03	< .509E-04	< .263E-04	< .382E-03
MOLYBDENUM	.803E-05	.183E-02	.000E+00	N .000E+00	.183E-02
NEODYMIUM	.000E+00	.304E-03	.000E+00	N .000E+00	.304E-03
NICKEL	.161E-03	U .000E+00	.113E-02	N .000E+00	.129E-02
NIOBIUM	.000E+00	.000E+00	.113E-03	N .000E+00	.113E-03
PHOSPHORUS	.238E-01	.365E-01	.000E+00	N .000E+00	.603E-01
POTASSIUM	.000E+00	.639E-01	> .594E+00	N .000E+00	> .658E+00
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	.113E-03	N .000E+00	.113E-03
SAMARIUM	< .402E-05	.000E+00	.000E+00	.000E+00	< .402E-05
SCANDIUM	.000E+00	.000E+00	< .565E-04	N .000E+00	< .565E-04
SELENIUM	.000E+00	.000E+00	.226E-01	N .000E+00	.226E-01
SILICON	U .000E+00	U .000E+00	.226E+00	N .000E+00	.226E+00
SILVER	.362E-04	.000E+00	.452E-02	N .000E+00	.456E-02
SODIUM	U .000E+00	.000E+00	> .537E+00	N .000E+00	> .537E+00
STRONTIUM	.402E-04	.304E-03	.565E-03	N .000E+00	.910E-03
SULFUR	> .370E-01	.213E-01	> .554E+00	N .000E+00	> .612E+00
TANTALUM	.000E+00	< .609E-03	.000E+00	N .000E+00	< .609E-03

COLT-SPARK
LOW-NOX

MASS/HEAT INPUT NG/J

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
TELLURIUM	.000E+00	.000E+00	.396E-03	N .000E+00	.396E-03
THORIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TIN	.201E-04	< .913E-03	.170E-03	N .000E+00	.190E-03<X<.110E-02
TITANIUM	.000E+00	.122E-01	.000E+00	N .000E+00	.122E-01
TUNGSTEN	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
VANADIUM	.000E+00	.609E-03	.565E-04	N .000E+00	.665E-03
YTTRIUM	.000E+00	.000E+00	< .565E-04	N .000E+00	< .565E-04
ZINC	.277E-02	.152E-01	.111E+00	N .000E+00	.129E+00
ZIRCONIUM	.000E+00	.000E+00	.170E-03	N .000E+00	.170E-03

COLT-SPARK
LOW-NOX

CONCENTRATION
MCG/DSCM

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
ALUMINUM	U .000E+00	.182E+02	U .000E+00	N .000E+00	.182E+02
ANTIMONY	< .599E-02	.000E+00	.000E+00	< .118E+00	< .124E+00
ARSENIC	.000E+00	.000E+00	< .843E-01	< .392E+00	< .476E+00
BARIUM	.000E+00	.454E+01	.000E+00	N .000E+00	.454E+01
BERYLLIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BISMUTH	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BORON	.599E+00	.363E+01	.000E+00	N .000E+00	.423E+01
BROMINE	.000E+00	.000E+00	.396E+01	N .000E+00	.396E+01
CADMIUM	< .599E-02	.000E+00	.000E+00	N .000E+00	< .599E-02
CALCIUM	U .000E+00	.272E+03	.000E+00	N .000E+00	.272E+03
CERIUM	.000E+00	.454E+00	.000E+00	N .000E+00	.454E+00
CESIUM	< .599E-02	.000E+00	< .843E-01	N .000E+00	< .903E-01
CHLORINE	.000E+00	.000E+00	.759E+02	N .000E+00	.759E+02
CHROMIUM	.359E+00	.771E+02	.160E+01	N .000E+00	.791E+02
COBALT	.000E+00	.272E+02	.000E+00	N .000E+00	.272E+02
COPPER	.180E+00	.186E+03	.842E+02	N .000E+00	.270E+03
FLUORINE	.237E+01	.000E+00	.169E+02	N .000E+00	.192E+02
GALLIUM	.000E+00	.908E+00	.169E+01	N .000E+00	.259E+01
GERMANIUM	< .599E-02	.000E+00	< .843E-01	N .000E+00	< .903E-01
GOLD	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
IODINE	.000E+00	.000E+00	.843E-01	N .000E+00	.843E-01
IRON	.120E+01	.163E+04	.000E+00	N .000E+00	.163E+04
LANTHANUM	.000E+00	.000E+00	.337E+01	N .000E+00	.337E+01
LEAD	.779E-01	.000E+00	.110E+02	N .000E+00	.110E+02
LITHIUM	.114E+00	.000E+00	.169E+00	N .000E+00	.282E+00
MAGNESIUM	.120E+02	.454E+01	.000E+00	N .000E+00	.165E+02
MANGANESE	.299E-01	.545E+02	.000E+00	N .000E+00	.545E+02
MERCURY	.000E+00	< .454E+00	< .759E-01	< .392E-01	< .569E+00
MOLYBDENUM	.120E-01	.272E+01	.000E+00	N .000E+00	.273E+01
NEODYMIUM	.000E+00	.454E+00	.000E+00	N .000E+00	.454E+00
NICKEL	.240E+00	U .000E+00	.169E+01	N .000E+00	.193E+01
NIOBIUM	.000E+00	.000E+00	.169E+00	N .000E+00	.169E+00
PHOSPHORUS	.355E+02	.545E+02	.000E+00	N .000E+00	.900E+02
POTASSIUM	.000E+00	.953E+02	> .885E+03	N .000E+00	> .980E+03
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	.169E+00	N .000E+00	.169E+00
SAMARIUM	< .599E-02	.000E+00	.000E+00	.000E+00	< .599E-02
SCANDIUM	.000E+00	.000E+00	< .843E-01	N .000E+00	< .843E-01
SELENIUM	.000E+00	.000E+00	.337E+02	N .000E+00	.337E+02
SILICON	U .000E+00	U .000E+00	.337E+03	N .000E+00	.337E+03
SILVER	.539E-01	.000E+00	.674E+01	N .000E+00	.680E+01
SODIUM	U .000E+00	.000E+00	> .801E+03	N .000E+00	> .801E+03
STRONTIUM	.599E-01	.454E+00	.843E+00	N .000E+00	.136E+01
SULFUR	> .551E+02	.318E+02	> .826E+03	N .000E+00	> .913E+03
TANTALUM	.900E+00	< .908E+00	.000E+00	N .000E+00	< .908E+00

COLT-SPARK
LOW-NOX

CONCENTRATION
MCG/DSCM

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
TELLURIUM	.000E+00	.000E+00	.590E+00	N .000E+00	.590E+00
THORIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TIN	.299E-01	< .136E+01	.253E+00	N .000E+00	.283E+00<X<.164E+01
TITANIUM	.000E+00	.182E+02	.000E+00	N .000E+00	.182E+02
TUNGSTEN	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
VANADIUM	.000E+00	.908E+00	.843E-01	N .000E+00	.992E+00
YTTRIUM	.000E+00	.000E+00	< .843E-01	N .000E+00	< .843E-01
ZINC	.413E+01	.227E+02	.166E+03	N .000E+00	.193E+03
ZIRCONIUM	.000E+00	.000E+00	.253E+00	N .000E+00	.253E+00

COLT-SPARK
LOW-NOX

MASS FLOW ELEMENT	MCG/SEC LUBE-OIL	FLUE GAS
ALUMINUM	> .149E+02	.436E+02
ANTIMONY	.000E+00	< .297E+00
ARSENIC	< .804E-01	< .114E+01
BARIUM	.402E+00	.109E+02
BERYLLIUM	.000E+00	.000E+00
BISMUTH	.000E+00	.000E+00
BORON	.161E+00	.102E+02
BROMINE	.121E+00	.952E+01
CADMIUM	< .281E-01	< .144E-01
CALCIUM	> .402E+02	.654E+03
CERIUM	.000E+00	.109E+01
CESIUM	.000E+00	< .217E+00
CHLORINE	.523E+01	.182E+03
CHROMIUM	.362E+01	.190E+03
COBALT	.241E+00	.654E+02
COPPER	.121E+01	.650E+03
FLUORINE	.121E+01	.462E+02
GALLIUM	.000E+00	.623E+01
GERMANIUM	.000E+00	< .217E+00
GOLD	.000E+00	.000E+00
IODINE	.804E-01	.203E+00
IRON	.121E+02	.393E+04
LANTHANUM	.000E+00	.810E+01
LEAD	.402E+00	.265E+02
LITHIUM	.804E-01	.679E+00
MAGNESIUM	> .402E+02	.397E+02
MANGANESE	.241E+00	.131E+03
MERCURY	< .402E-01	< .137E+01
MOLYBDENUM	.322E+00	.657E+01
NEODYMIUM	.000E+00	.109E+01
NICKEL	.402E+00	.463E+01
NIOBIUM	.000E+00	.405E+00
PHOSPHORUS	> .402E+02	.216E+03
POTASSIUM	.185E+02	> .236E+04
PRASEODYMIUM	.000E+00	.000E+00
RUBIDIUM	.281E-01	.405E+00
SAMARIUM	.000E+00	< .144E-01
SCANDIUM	< .161E-01	< .203E+00
SELENIUM	.000E+00	.810E+02
SILICON	.173E+02	.810E+03
SILVER	.000E+00	.163E+02
SODIUM	> .386E+02	> .192E+04
STRONTIUM	.804E+00	.326E+01
SULFUR	> .402E+02	> .219E+04
TANTALUM	.000E+00	< .218E+01

COLT-SPARK
LOW-NOX

MASS FLOW ELEMENT	MCG/SEC LUBE-OIL	FLUE GAS
TELLURIUM	.000E+00	.142E+01
THORIUM	.000E+00	.000E+00
TIN	.362E+00	.680E+00<X<.395E+01
TITANIUM	.362E+01	.436E+02
TUNGSTEN	.000E+00	.000E+00
URANIUM	.000E+00	.000E+00
VANADIUM	.241E-01	.238E+01
YTTRIUM	.000E+00	< .203E+00
ZINC	> .402E+02	.464E+03
ZIRCONIUM	.000E+00	.608E+00

COLT-SPARK
LOW-NOX

MASS FLOW
MCG/SEC

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
ALUMINUM	U .000E+00	.436E+02	U .000E+00	N .000E+00	.436E+02
ANTIMONY	< .144E-01	.000E+00	.000E+00	< .282E+00	< .297E+00
ARSENIC	.000E+00	.000E+00	< .203E+00	< .942E+00	< .114E+01
BARIUM	.000E+00	.109E+02	.000E+00	N .000E+00	.109E+02
BERYLLIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BISMUTH	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
BORON	.144E+01	.872E+01	.000E+00	N .000E+00	.102E+02
BROMINE	.000E+00	.000E+00	.952E+01	N .000E+00	.952E+01
CADMIUM	< .144E-01	.000E+00	.000E+00	N .000E+00	< .144E-01
CALCIUM	U .000E+00	.654E+03	.000E+00	N 000E+00	.654E+03
CERIUM	.000E+00	.109E+01	.000E+00	N 000E+00	.109E+01
CESIUM	< .144E-01	.000E+00	< .203E+00	N .000E+00	< .217E+00
CHLORINE	.000E+00	.000E+00	.182E+03	N .000E+00	.182E+03
CHROMIUM	.864E+00	.185E+03	.385E+01	N .000E+00	.190E+03
COBALT	.000E+00	.654E+02	.000E+00	N .000E+00	.654E+02
COPPER	.432E+00	.447E+03	.202E+03	N .000E+00	.650E+03
FLUORINE	.569E+01	.000E+00	.405E+02	N .000E+00	.462E+02
GALLIUM	.000E+00	.218E+01	.405E+01	N .000E+00	.623E+01
GERMANIUM	< .144E-01	.000E+00	< .203E+00	N .000E+00	< .217E+00
GOLD	.000E+00	.000E+00	.000E+00	N 000E+00	.000E+00
IODINE	.000E+00	.000E+00	.203E+00	N .000E+00	.203E+00
IRON	.288E+01	.393E+04	.000E+00	N .000E+00	.393E+04
LANTHANUM	.000E+00	.000E+00	.810E+01	N .000E+00	.810E+01
LEAD	.187E+00	.000E+00	.263E+02	N .000E+00	.265E+02
LITHIUM	.273E+00	.000E+00	.405E+00	N .000E+00	.679E+00
MAGNESIUM	.288E+02	.109E+02	.000E+00	N .000E+00	.397E+02
MANGANESE	.720E-01	.131E+03	.000E+00	N .000E+00	.131E+03
MERCURY	.000E+00	< .109E+01	< .182E+00	< .942E-01	< .137E+01
MOLYBDENUM	.288E-01	.654E+01	.000E+00	N 000E+00	.657E+01
NEODYMIUM	.000E+00	.109E+01	.000E+00	N 000E+00	.109E+01
NICKEL	.576E+00	U .000E+00	.405E+01	N .000E+00	.463E+01
NIOBIUM	.000E+00	.000E+00	.405E+00	N .000E+00	.405E+00
PHOSPHORUS	.854E+02	.131E+03	.000E+00	N .000E+00	.216E+03
POTASSIUM	.000E+00	.229E+03	> .213E+04	N .000E+00	> .236E+04
PRASEODYMIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
RUBIDIUM	.000E+00	.000E+00	.405E+00	N .000E+00	.405E+00
SAMARIUM	< .144E-01	.000E+00	.000E+00	.000E+00	< .144E-01
SCANDIUM	.000E+00	.000E+00	< .203E+00	N .000E+00	< .203E+00
SELENIUM	.000E+00	.000E+00	.810E+02	N .000E+00	.810E+02
SILICON	U .000E+00	U .000E+00	.810E+03	N .000E+00	.810E+03
SILVER	.130E+00	.000E+00	.162E+02	N .000E+00	.163E+02
SODIUM	U .000E+00	.000E+00	> .192E+04	N .000E+00	> .192E+04
STRONTIUM	.144E+00	.109E+01	.203E+01	N .000E+00	.326E+01
SULFUR	> .132E+03	.763E+02	> .199E+04	N .000E+00	> .219E+04
TANTALUM	.000E+00	< .218E+01	.000E+00	N .000E+00	< .218E+01

COLT-SPARK
LOW-NOX

MASS FLOW
MCG/SEC

ELEMENT	FILTER	XAD	IMPINGER 1+OMC	IMPINGER 2+3	FLUE GAS
TELLURIUM	.000E+00	.000E+00	.142E+01	N .000E+00	.142E+01
THORIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
TIN	.720E-01	< .327E+01	.608E+00	N .000E+00	.680E+00<X<.395E+01
TITANIUM	.000E+00	.436E+02	.000E+00	N .000E+00	.436E+02
TUNGSTEN	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
URANIUM	.000E+00	.000E+00	.000E+00	N .000E+00	.000E+00
VANADIUM	.000E+00	.218E+01	.203E+00	N .000E+00	.238E+01
YTTRIUM	.000E+00	.000E+00	< .203E+00	N .000E+00	< .203E+00
ZINC	.993E+01	.545E+02	.399E+03	N .000E+00	.464E+03
ZIRCONIUM	.000E+00	.000E+00	.608E+00	N .000E+00	.608E+00

COLT-SPARK
LOW-NOX

ENGINE MASS-BALANCE
INPUT=LUBE-OIL 0UTPUT=EXHAUST

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
ALUMINUM	.149E+02 <X	.436E+02	X<.293E+01
ANTIMONY		X<.297E+00	*
ARSENIC	X<.804E-01	X<.114E+01	*
BARIUM	.402E+00	.109E+02	.271E+02
BERYLLIUM			*
BISMUTH			*
BORON	.161E+00	.102E+02	.632E+02
BROMINE	.121E+00	.952E+01	.789E+02
CADMIUM	X<.281E-01	X<.144E-01	*
CALCIUM	.402E+02 <X	.654E+03	X<.163E+02
CERIUM		.109E+01	*
CESIUM		X<.217E+00	*
CHLORINE	.523E+01	.182E+03	.349E+02
CHROMIUM	.362E+01	.190E+03	.525E+02
COBALT	.241E+00	.654E+02	.271E+03
COPPER	.121E+01	.650E+03	.539E+03
FLUORINE	.121E+01	.462E+02	.383E+02
GALLIUM		.623E+01	*
GERMANIUM		X<.217E+00	*
GOLD			*
IODINE	.804E-01	.203E+00	.252E+01
IRON	.121E+02	.393E+04	.326E+03
LANTHANUM		.810E+01	*
LEAD	.402E+00	.265E+02	.660E+02
LITHIUM	.804E-01	.679E+00	.844E+01
MAGNESIUM	.402E+02 <X	.397E+02	X<.987E+00
MANGANESE	.241E+00	.131E+03	.543E+03
MERCURY	X<.402E-01	X<.137E+01	*
MOLYBDENUM	.322E+00	.657E+01	.204E+02
NEODYMIUM		.109E+01	*
NICKEL	.402E+00	.463E+01	.115E+02
NIOBIUM		.405E+00	*
PHOSPHORUS	.402E+02 <X	.216E+03	X<.538E+01
POTASSIUM	.185E+02	.236E+04 <X	127E+03 <X
PRASEODYMIUM			*
RUBIDIUM	.281E-01	.405E+00	.144E+02
SAMARIUM		X<.144E-01	*
SCANDIUM	X<.161E-01	X<.203E+00	*
SELENIUM		.810E+02	*
SILICON	.173E+02	.810E+03	.469E+02
SILVER		.163E+02	*
SODIUM	.386E+02 <X	.192E+04 <X	*
STRONTIUM	.804E+00	.326E+01	.405E+01
SULFUR	.402E+02 <X	.219E+04 <X	*
TANTALUM		X<.218E+01	*

COLT-SPARK
LOW-NOX

ENGINE MASS-BALANCE
INPUT=LUBE-OIL 0UTPUT=EXHAUST

ELEMENT	TOTAL IN	TOTAL OUT	MASS BALANCE (OUT/IN)
TELLURIUM		.142E+01	*
THORIUM			*
TIN	.362E+00	.680E+00<X<.395E+01	.188E+01<X<.109E+02
TITANIUM	.362E+01	.436E+02	.121E+02
TUNGSTEN			*
URANIUM			*
VANADIUM	.241E-01	.238E+01	.988E+02
YTTRIUM		X<.203E+00	*
ZINC	.402E+02 <X	.464E+03	X<.115E+02
ZIRCONIUM		.608E+00	*

APPENDIX C

CONVERSION UNITS AND SAMPLE CALCULATIONS

Conversion Units		
To Obtain	Multiply	By
Watt (W)	Bhp	746
Joules (output)	Bhp-hr	2.68×10^6
Joules	Btu	1,055
g	lb	454
g/kW-hr	lb/Bhp-hr	609
Pa	psi	6,895
l/s	gpm	6.31×10^{-2}
Kg/s	lb/min	7.58×10^{-3}
ng/J (input)	$lb/10^6$ Btu (input) g/Bhp-hr (output)	430 372E
Where E = engine efficiency		
K = (°F + 460)/1.8		

Sample Calculations:

a) BSFC $= \frac{W_f\ (60)}{Bhp}$

b) CID/cyl $= \frac{\pi\ (\text{cylinder bore diameter})^2 \times \text{stroke} \times 2}{4}$

c) BMEP $= \frac{Bhp\ (33000)(12)}{\frac{CID}{Cyl}\ (\text{Number of cylinders})\ \frac{RPM}{2}}$

d) BS(a)dry basis $= 4.54 \times 10^{-6} \times MW\ (a) \times NTD' \times ppm\ (dry) \times BSFC$

where:

NTD' = moles of dry exhaust products / 100 pounds of fuel

e) Correction of NO_x/NO to standard atmospheric conditions of 10.71g H_2O/kg air (75 grains/lb air) humidity and 302K (85°F) ambient temperature:

NO_x corrected = $NO_x \times K_1$

where:

$K_1 = 1/(1- 0.00235\ (H-75) + 0.00220\ (T-85))$

and

H = observed humidity in grains H_2O / pound of dry air

T = observed inlet air temperature in °F

APPENDIX D

GLOSSARY OF ACRONYMS

AAS - Atomic Absorption Spectroscopy

A/F - Air-to-fuel ratio - weight basis

Bhp - Brake horsepower

BMEP - Brake mean effective pressure

BMV - Before minimum (cylinder) volume

BS(a) - Brake specific emissions - grams of pollutant (a) produced by the engine in developing 1 Bhp-hr

BSFC - Brake specific fuel consumption in Btu of fuel per Bhp-hr

CID/cyl - Cubic inches piston displacement per cylinder. Since opposed piston engine has two pistons per cylinder, the total CID/cyl is twice the displacement of each piston

DEMA - Diesel Engine Manufacturers Association

DSCM - Dry standard cubic meter

FID - Flame ionization detector

GC - Gas chromatography

GC/MS - Gas chromatography/mass spectroscopy

MW(a) - Molecular weight of pollutant (a)

NDIR - Nondispersive infrared

POM - Polycyclic organic matter

RPM - Revolutions per minute - engine speed

SASS - Source assessment sampling system

SSMS - Spark source mass spectroscopy

W_f - Weight of fuel flow, pounds per hour